A revision of the Inert Doublet Model

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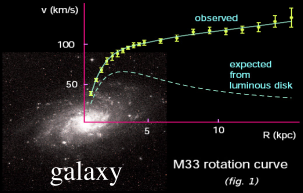
based on:

The Inert Doublet Model: An Archetype for Dark Matter:JCAP 0702:028
Scalar Multiplet Dark Matter: JHEP 0907:090
The inert doublet model of dark matter revisited:JHEP 1009:046
A new viable region of the inert doublet model: JCAP 1101:002

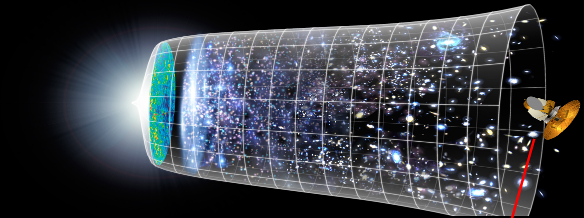
in collaboration with

T. Hambye, F. S. Ling, E. Nezri, J. Rocher, M. Tytgat, C. Yaguna

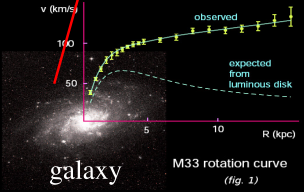
Séminaire LAPTH
Laboratoire d'Annecy-le-Vieux de Physique Théorique



The Quest to determine the Composition of our Universe



Dark matter



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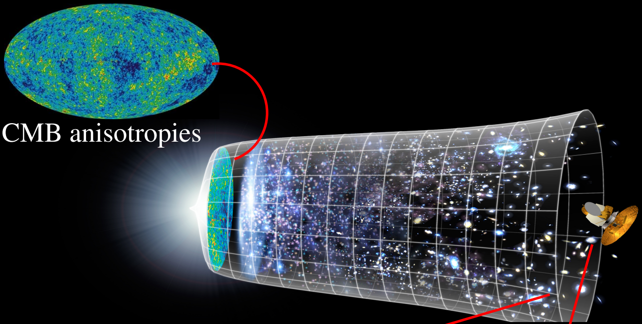
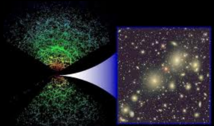


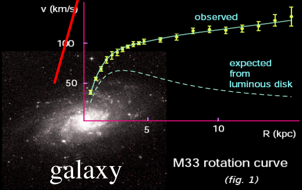
CMB anisotropies

Large Scale Structures (LSS)



SDSS galaxy map

Dark matter



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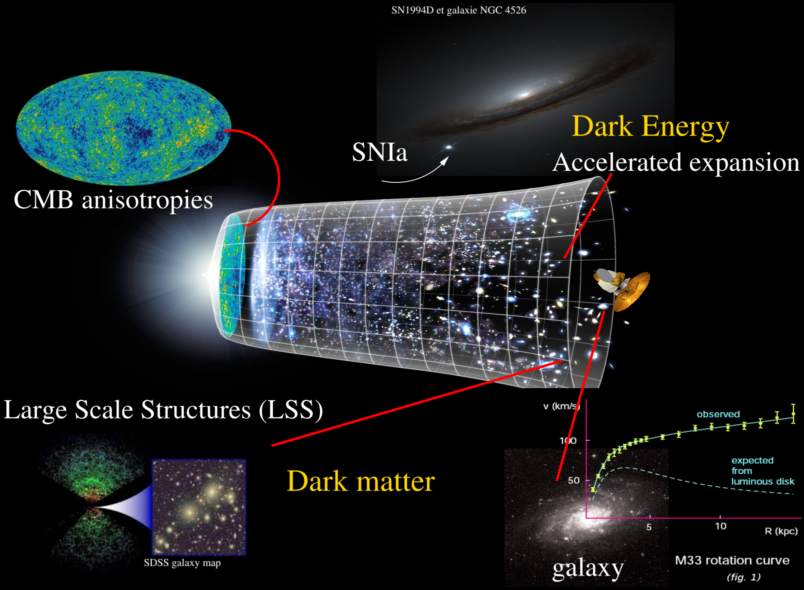

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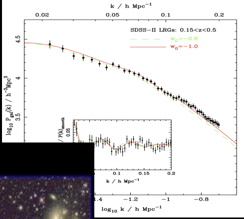
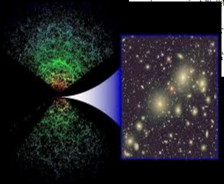
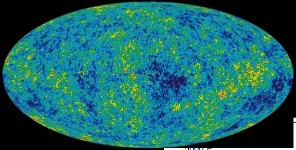
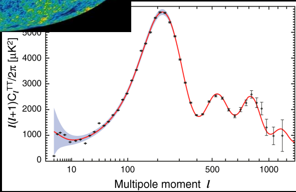
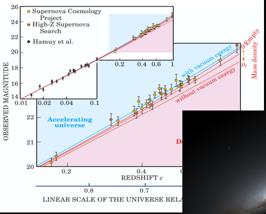
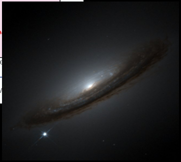

k / h Mpc^{-1}
0.02 0.05 0.1 0.2
SDSS−II LRGs: 0.15<z<0.5
w$_0$=−0.8
w$_0$=−1.0
log$_{10}$ P$_{gal}$(k) / h^{-3}Mpc^3
4.5 4 3.5
0.1 0.15 0.2
k / h Mpc^{-1}
−1.2 −1 −0.8
log$_{10}$ k / h Mpc^{-1}





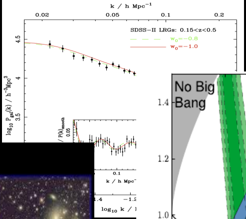

$l(l+1)C_l^{TT}/2\pi$ [μK^2]
0 1000 2000 3000 4000 5000
10 100 500 1000
Multipole moment l

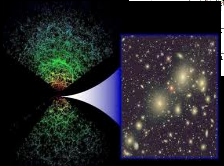

Supernova Cosmology Project
High-Z Supernova Search
Hamuy et al.
OBSERVED MAGNITUDE
26 24 22 20 18 16 14
0.01 0.02 0.04 0.1
0.2 0.4 0.6 1
with vacuum energy
without vacuum energy
Empty
Mass density
Accelerating universe
22 21 20
0.2 0.4
REDSHIFT z
0.8 0.7
LINEAR SCALE OF THE UNIVERSE REL

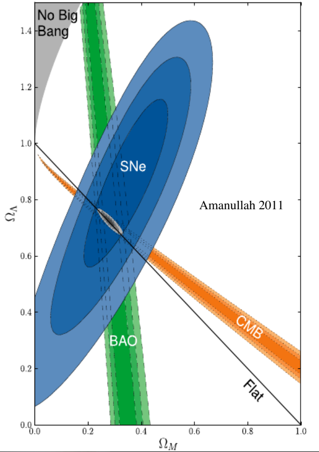


SDSS

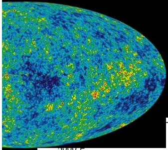
Percival et al 2010

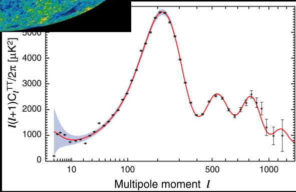




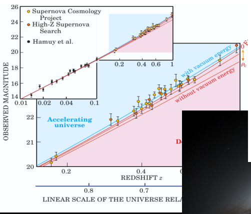


Amanullah 2011

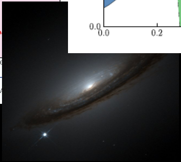




WMAP7, Larson et al 2010



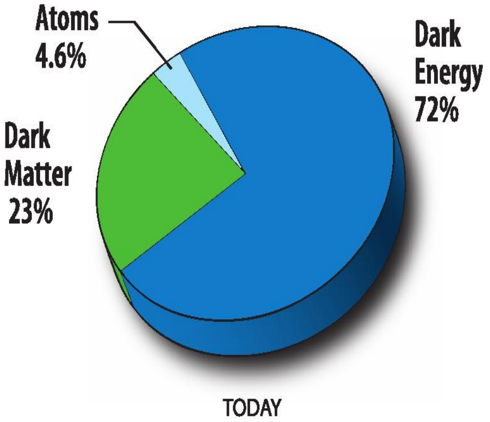
Pelmutter 2003



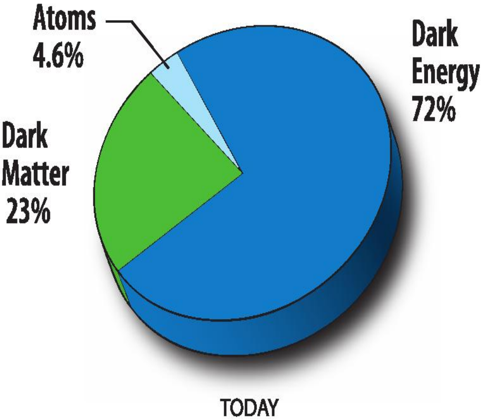
Concordance for a flat Universe today made of

~ 70% of dark energy as a Cosmo. Cst.

~ 30% of matter


Atoms
4.6%
Dark
Energy
72%
Dark
Matter
23%
TODAY

In other words $\Omega_{dm} h^2 = 0.1099$ (WMAP5)



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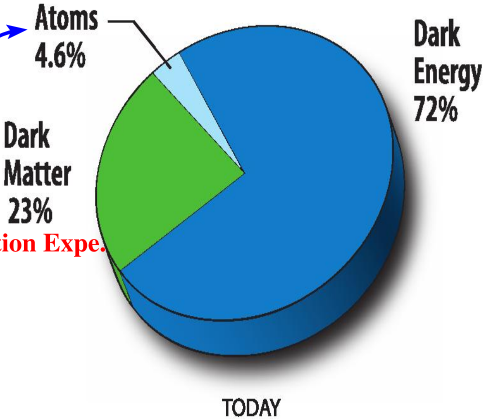
In this TALK! Scalar DM Model Viable param. space



+ Constraints from DM detection Expe.

WIMP as dark matter

Minimal DM spirit : SM + one $SU(2)_L$ n-uplet see Cirelli *et* all '05-'09

- DM = neutral member of the n-uplet
- stability $\rightsquigarrow$ usually extra Z_2 symmetry

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- Fermion multiplets : very predictive
    - all (co)annihilation are *known* gauge $SU(2)_L \times U(1)$ processes
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- Scalar multiplets H_n :
  - extra quartic coupling λ_i to Higgs H_1
  - a *range* free parameters : $\{m_{DM}, \lambda_i\}$ is compatible with Ω_{DM}^{WMAP}

Scalar DM model

- Extra n-uplet case ($n > 2$) :
  - only one coupling to the Higgs $\lambda_3 |H_1|^2 |H_n|^2$
  - no mass splittings between H_n^0 and $H_n^{\pm(\ldots\pm)}$

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- Particular case : $n = 2 \equiv$ IDM
  - three couplings to the Higgs.

$$\lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} \left[(H_1^\dagger H_2)^2 + h.c. \right]$$

  - non zero mass splittings :

$$H_2 = \begin{pmatrix} iH^+ \\ \frac{(H_0 - iA_0)}{\sqrt{2}} \end{pmatrix} \quad H_1 = \begin{pmatrix} 0 \\ \frac{(h + v_0)}{\sqrt{2}} \end{pmatrix}$$

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

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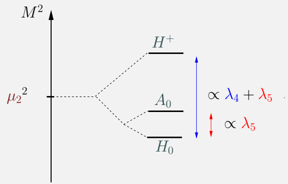
$${m_\chi}^2 = \mu_2^2 + \lambda_\chi v_0^2$$



$$\lambda_{H_c} \equiv \lambda_3/2$$

$$\lambda_{H_0,A_0} \equiv (\lambda_3 + \lambda_4 \pm \lambda_5)/2$$

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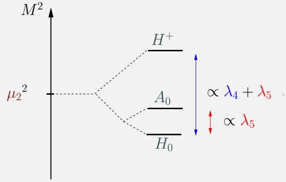
$\rightsquigarrow$ viable mass ranges $m_{H_0} \sim$ GeV-TeV range

We will refer to $H_0 - h$ coupling as $\lambda_{H_0} = \lambda_L$

Free parameters : $m_{H_0}, m_h, \lambda_L, \Delta m_{A^0}, \Delta m_{H^+}$

$$m_\chi{}^2 = \mu_2^2 + \lambda_\chi v_0^2$$



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More on the Inert doublet model

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- Relic Density : Freeze-out mechanism $\Omega h^2 \propto 1/\langle \sigma v_{eff} \rangle$
  Including $H_0 H_0 \to XX$ and $H_0 A_0, H_0 H^\pm \to XX$
  using `micrOMEGAs` G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov,...

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  using `micrOMEGAs` G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov,...
- Extra Constraints
  - Vacuum stability : $\lambda_1, \lambda_2 > 0$ and $\lambda_L, \lambda_3 > -2\sqrt{\lambda_1 \lambda_2}$
  - Perturbativity : strong couplings $|\lambda| > 4\pi$ are excluded
  - No new contribution to the Z decay
  - No new low mass charged particles : $m_{H^\pm} > 90$ GeV see e.g. Pierce & Thaler JHEP07
  - $\sigma_{H_0 - p}$ below the existing limits from direct detection searches
    $\rightsquigarrow$ Need a splitting $m_{A_0} - m_{H_0} \neq 0$
  - EWPT measurements : heavy higgs allowed [Barbieri et al '06]
    $\rightsquigarrow$ need $m_{H_0} - m_{H^\pm} \neq 0$ and $m_{A_0} - m_{H^\pm} \neq 0$ with $m_{H^\pm} > m_{H_0}, m_{A_0}$

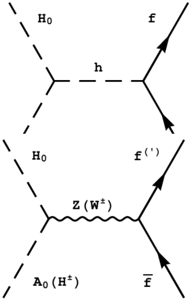
A first systmatic study of the viable parameter space

based on LLH, Nezri, Oliver, Tytgat JCAP07

- $m_{H_0} \lesssim m_W$: GeV range

$$H_0 H_0 \rightarrow h^* \rightarrow \bar{f}f \text{ and } H_0 A_0 \rightarrow Z^* \rightarrow \bar{f}f$$

Barbieri PRD06, LLH JCAP06,Gustafsson PRL07, Cao PRD07, Andreas JCAP08,...



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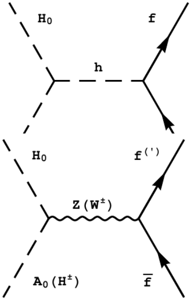

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- $m_{H_0} \gg m_W$: TeV range
  $H_0 H_0 \to ZZ, WW, hh$ and coannihil into bosons

  Cirelli NPB06, Hambye JHEP09

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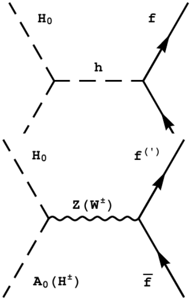

LARGE MASS GAP DUE TO EFFICIENT
WW AND *ZZ* ANNIHILATION

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The High mass regime

based on: Scalar Multiplet Dark Matter
Hambye, Ling, LLH, J. Rocher

JHEP 09

IDM in the High mass regime : Relic abundance

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Quartic couplings OFF : pure gauge

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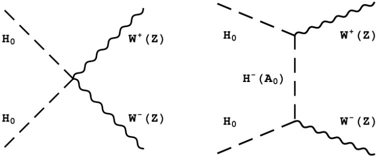
e.g. contribution to σ_g^{00} : $H_0 H_0 \to XX$



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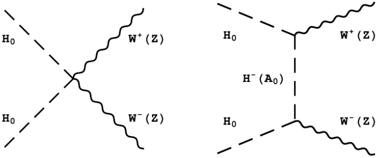

$$\sigma_{\text{eff}} = \sum_{ij} \sigma_g^{ij} \propto \frac{g^4}{m_{H_0}^2}$$

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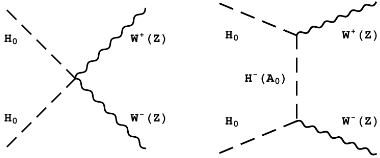

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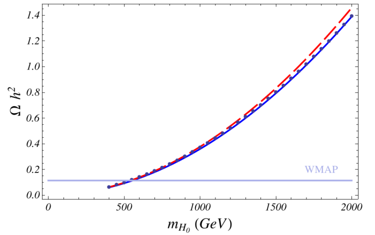


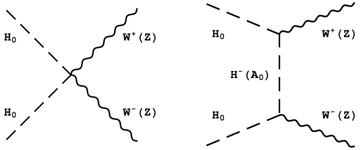
$\rightsquigarrow$ Only $m_{H_0} = m^* \sim 534$ GeV satisfy WMAP

in agreement with Cirelli *et* all '05

IDM in the High mass regime : Relic abundance

Quartic couplings ON : extra Higgs processes and $m_{H_0} \neq m_{A_0} \neq m_{H_c}$

for *e.g.* $H_0 H_0 \to XX$



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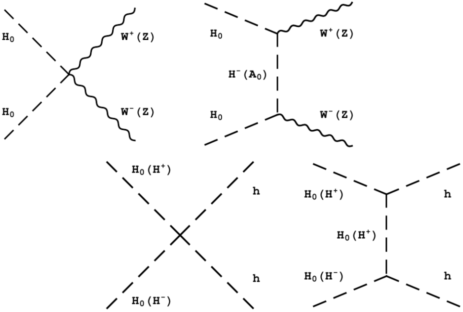

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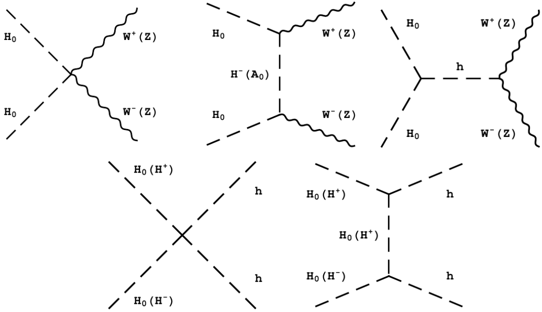

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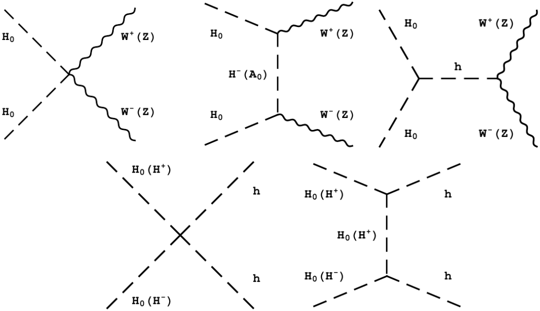
$$\sigma_{\rm eff} = \sum_{ij} \left(\sigma_g^{ij} + \sigma_\lambda^{ij} \right) \propto \frac{1}{m_{H_0}^2}$$

where $\sigma_\lambda^{ij} = \frac{\Lambda^{ij}}{m_{H_0}^2}$ with $\Lambda^{ij} \propto \lambda * \lambda$ and $\Lambda^{ij} > 0$

for *e.g.* $H_0 H_0 \to XX$



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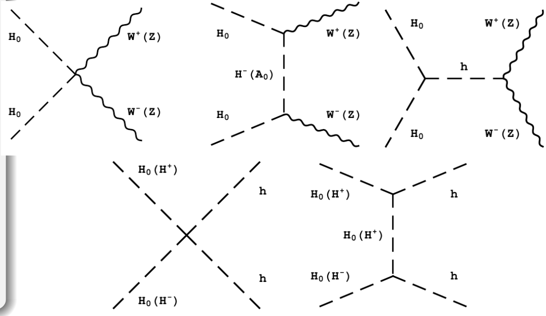
$$\text{where } \sigma_\lambda^{ij} = \frac{\Lambda^{ij}}{m_{H_0}^2} \text{ with } \Lambda^{ij} \propto \lambda * \lambda \text{ and } \Lambda^{ij} > 0$$

- $m^* \sim 534$ GeV is minimal to satisfy WMAP

for *e.g.* $H_0 H_0 \to XX$



IDM in the High mass regime : Relic abundance

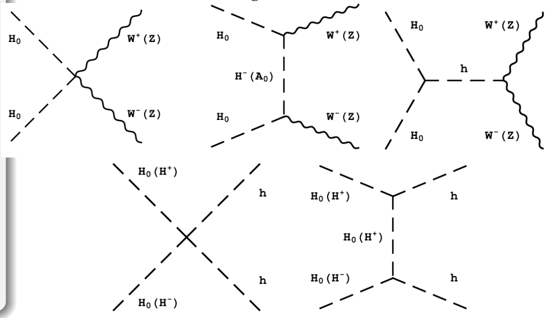
Quartic couplings ON : extra Higgs processes and $m_{H_0} \neq m_{A_0} \neq m_{H_c}$

$$\sigma_{\rm eff} = \sum_{ij} \left(\sigma_g^{ij} + \sigma_\lambda^{ij}\right) \propto \frac{1}{m_{H_0}^2}$$

where $\sigma_\lambda^{ij} = \frac{\Lambda^{ij}}{m_{H_0}^2}$ with $\Lambda^{ij} \propto \lambda * \lambda$ and $\Lambda^{ij} > 0$

- $m^* \sim 534$ GeV is minimal to satisfy WMAP
- for fixed m_{H_0} and $\sigma_{\rm eff}$ λ_i lie on ellipsoid surface

for *e.g.* $H_0 H_0 \to XX$



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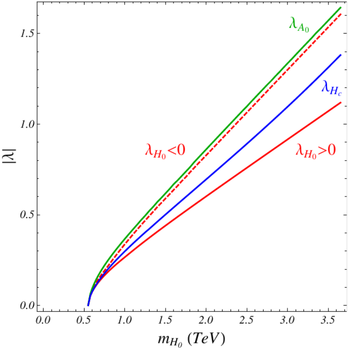

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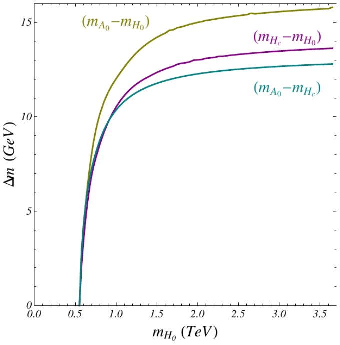
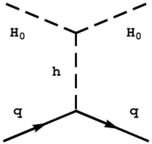
- mass splittings are also bounded as $m_i - m_j \propto (\lambda_i - \lambda_j)/m_{H_0}$



Prospects for Direct and Indirect detection

Direct detection through Elastic Scattering ($m_{A_0} - m_{H_0}$ >150 keV)



$$\sigma_{el} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2}\right)^2$$

$M_{H_0} \propto \lambda_{H_0} \rightsquigarrow \sigma_{el} < 9.410^{-9}$ pb

bounded $\lambda_{H_0} \rightsquigarrow$ absolute upper bound

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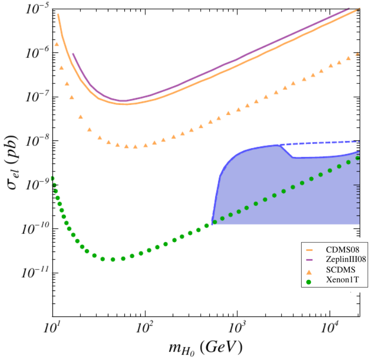
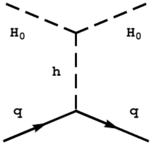


m_h = 120 GeV for illustration



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Cancellations above W threshold

based on:

A new viable region of the inert doublet model: JCAP 1101:002

LLH & Yaguna

Inert doublet model viable parameter space

- $m_{H_0} \lesssim m_W$: GeV range

  $H_0 H_0 \to h^* \to \bar{f}f$ and $H_0 A_0 \to Z^* \to \bar{f}f$

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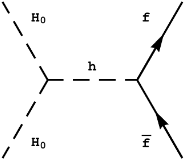

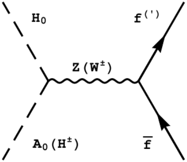

LARGE MASS GAP DUE TO EFFICIENT
WW AND *ZZ* ANNIHILATION

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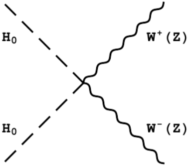

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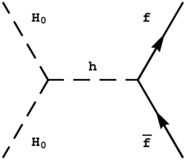

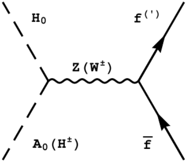

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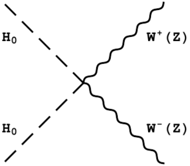
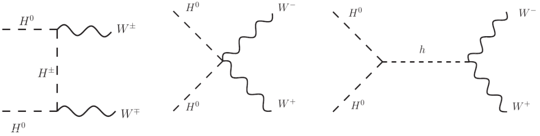


Illustration of cancellation in 2 body processes



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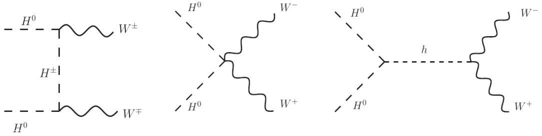
For $m_W \sim m_{H^0}$ destructive interf. :

$$\lambda_L \simeq \frac{-2(m_{H^0}^2 - (M_h/2)^2)}{v^2}$$

- $\lambda_L < 0$ for $m_{H^0} > M_h/2$
- $\lambda_L > 0$ for $m_{H^0} < M_h/2$

always need : $m_{H^0} < M_h, m_t$



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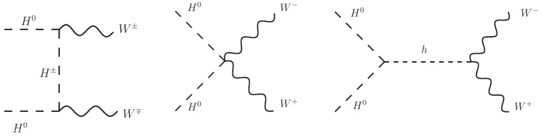

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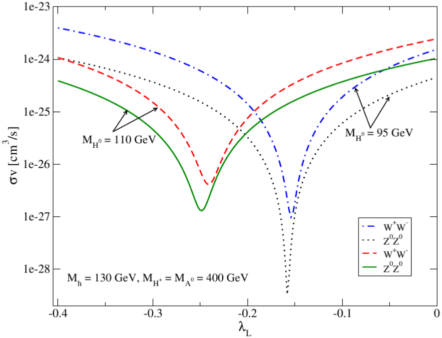

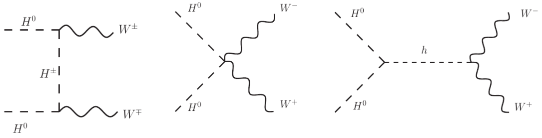

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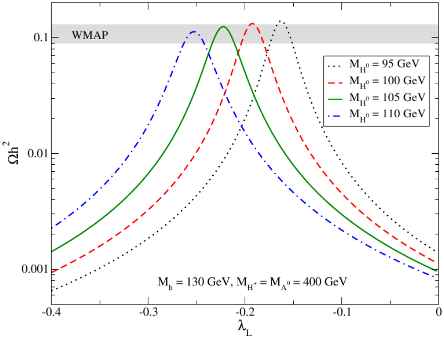
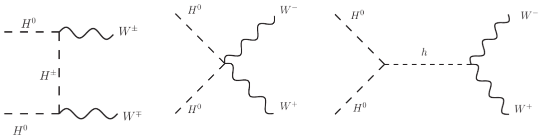




New viable parameter space thanks to cancellations

Result of a scan for $m_{H^0} > m_W$ and $\Omega_{H_0} = \Omega_{WMAP}$

$\lambda_L > 0$ $M_{Ho} < M_h/2$

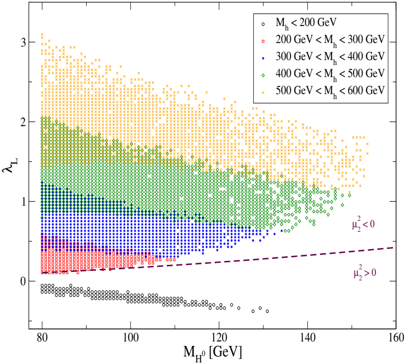
200 GeV < M_h < 600 GeV

up to M_{Ho} ~ 160 GeV

$\lambda_L < 0$ $M_{Ho} > M_h/2$

for M_h < 200 GeV

up to M_{Ho} =130 GeV



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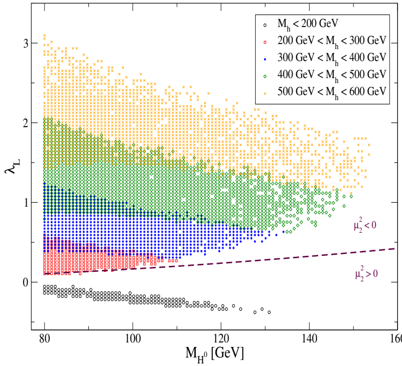
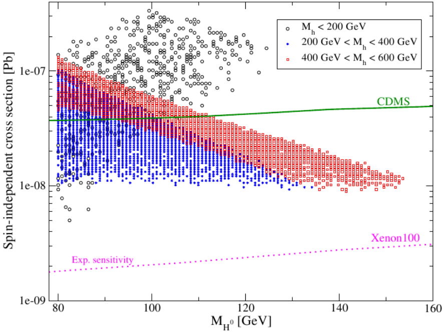


NB : IDM can comply with EWPT measurements for large M_h as Barbieri '06 :
$\Delta T_{H_0,H^+,A_0}$ can compensate negative T_h for $m_{H^+} > m_{A_0}, m_{H^0}$

Direct Detection searches

... A very efficient probe of the $m_{H^0} > m_W$ parameter space :



Remember :

$$\sigma_{H_0-N} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2}\right)^2$$

and for cancellations,
λ_L is necessarily non zero

$\rightsquigarrow$ a large fraction of the parameter space is already ruled out by CDMS Ahmed '10
the remaining viable param. space is within the reach of Xenon 100 Aprile '10

Extra contributions from 3 body annihilations

based on:

A new viable region of the inert doublet model: JHEP 1009:046

LLH & Yaguna

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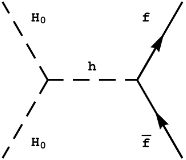
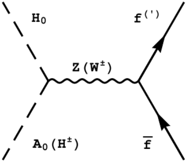
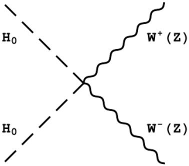




LARGE MASS GAP DUE TO EFFICIENT
WW AND *ZZ* ANNIHILATION



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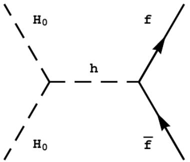

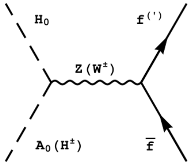

- Above W-threshold : cancellations

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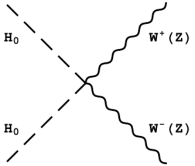

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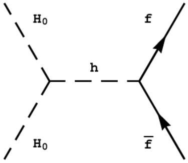
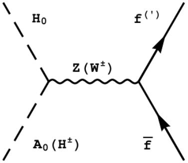


Significantly affected by 3bdy annihilation :

$$H_0 H_0 \to WW^* \to W\bar{f}f'$$



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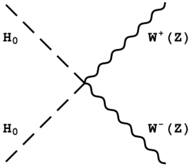

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Cirelli NPB06, Hambye JHEP09

Importance of 3-body processes : Is that so surprising ?

3-body processes can take over 2-body processes

3-body $\equiv$ real + virtual massive particle

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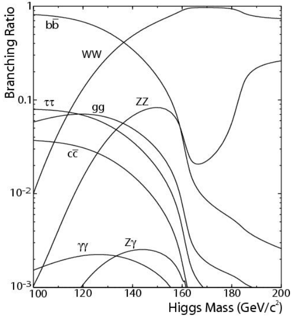
Well known example : higgs decay

$\text{BR}(h \to WW^*) \gg \text{BR}(h \to \bar{b}b)$ for $m_h \lesssim 2M_W$



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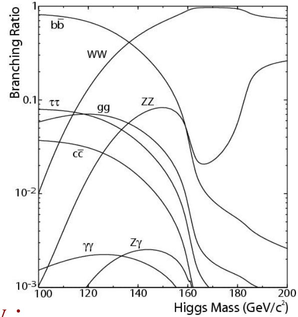

3-body processes can enhance DM annihilation/decay :

$\rightsquigarrow$ Affect relic abundance, viable parameter space, detection

$\rightsquigarrow$ Significant effect on : neutralino LSP [Chen & Kamionkowski JHEP '98, Yaguna PRD'10],
gravitino LSP [Choi & Yaguna '1003,& all '1007],
Higgs DM [Hosotani, Ko & Tanaka PLB'09], singlet scalar DM [Yaguna PRD'10],
Inert Doublet Model [LLH & Yaguna JHEP'10]

Extra contributions from 3 body annihilations

Analysis for fixed parameters

2-3 body annihilation cross section near m_W threshold

- σv_{2bdy} : higgs mediated,
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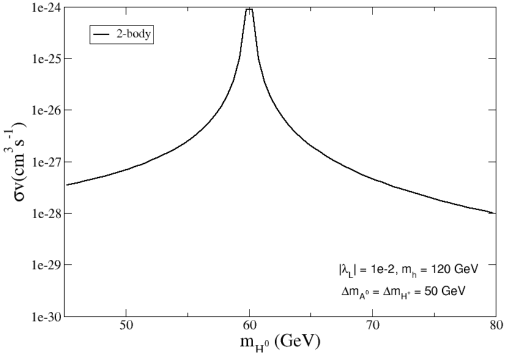

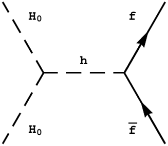

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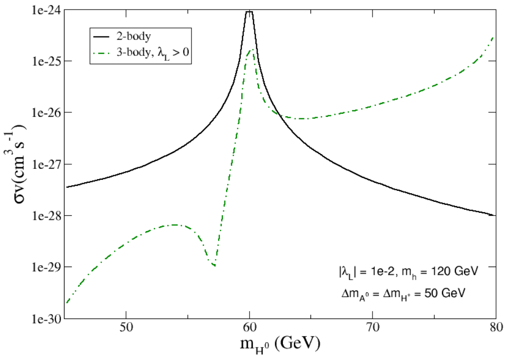

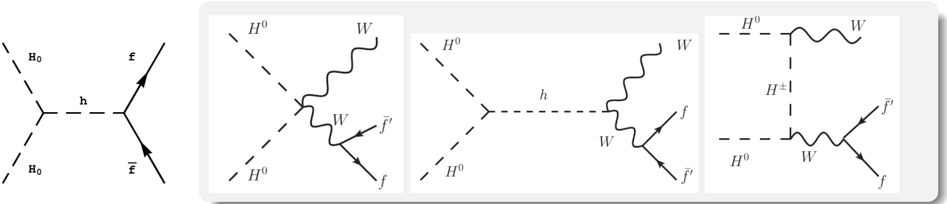

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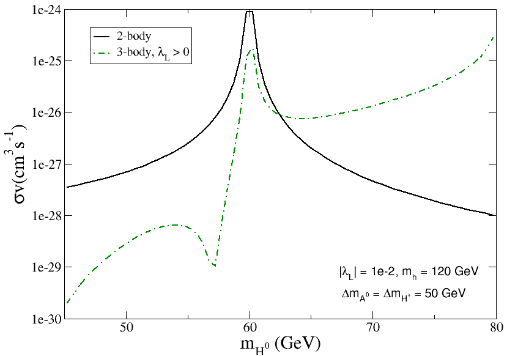
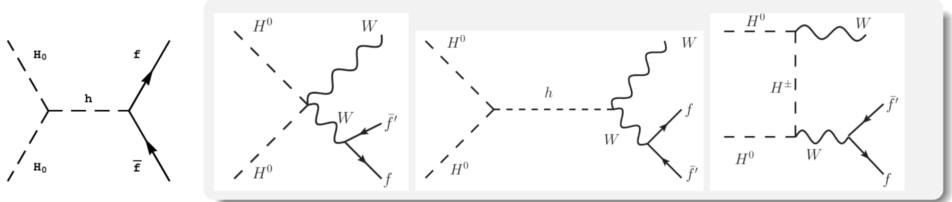
⇝ σv_{2bdy} vs σv_{3bdy} depends on m_{H^0}, m_h, λ_L sign and amplitude





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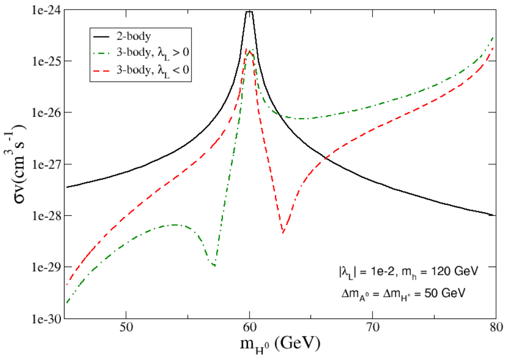
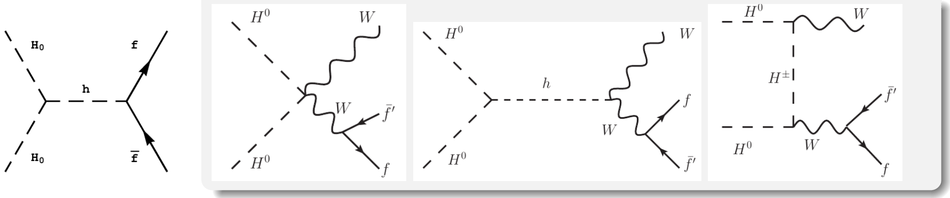
$\rightsquigarrow$ σv_{2bdy} vs σv_{3bdy} depends on m_{H^0}, m_h, λ_L sign and amplitude





2-3 body annihilation cross section near m_W threshold

- σv_{2bdy} : higgs mediated,
  $\rightsquigarrow$ suppressed by Yukawa, m_h
- $\sigma v_{3bdy} = \sigma v(WW^*)$
  $\rightsquigarrow$ high multiplicity
  $\rightsquigarrow$ gauge unsuppressed

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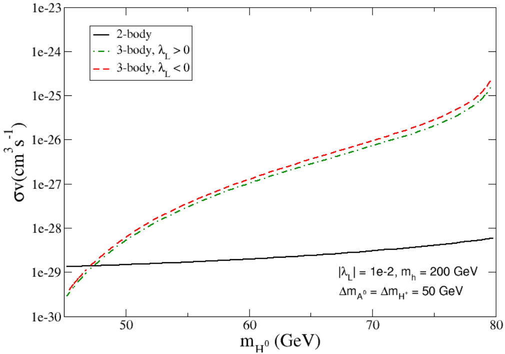

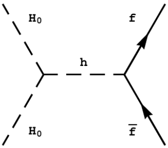

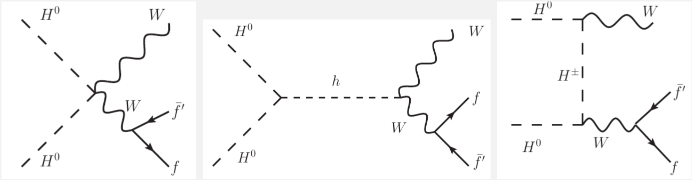

Comparing 2-3 body relic density

In the absence of coannihilations :

- roughly $\Omega_{dm} \propto 1/\langle\sigma \text{v}\rangle$ with
$\langle\sigma \text{v}\rangle = \langle\sigma \text{v}(\text{ 2-body})\rangle + \langle\sigma \text{v}(WW^*)\rangle$
- We expect
Ω_{dm}(3-body)$\lesssim$ Ω_{dm}(2-body)

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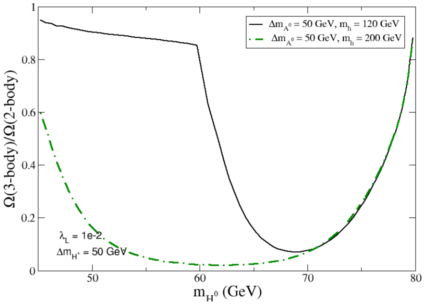
$\rightsquigarrow$ confirmed numerically using modified micrOMEGAs



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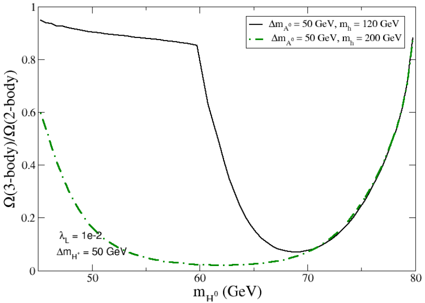

$\rightsquigarrow$ 3-body final states significantly affect predictions for Ω_{dm}

Comparing 2-3 body relic density

Ω_{dm} is Δm dependent $\leftrightarrow$ allows coannihilations

Including coannihilations

:

- coannihilations $\equiv$ 2-bdy pure gauge process $H_0 A_0 \to Z \to \bar{f}f$
- Including coannihilations can change the impact of the 3-bdy processes

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$(\Delta m_{A^0} = 10, \Delta m_{H^+} = 50 \text{ GeV})$:

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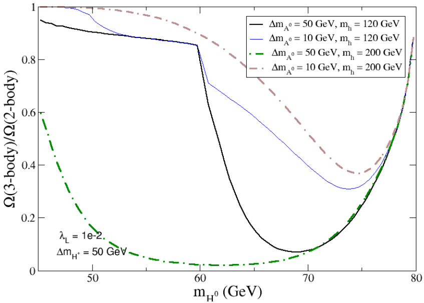

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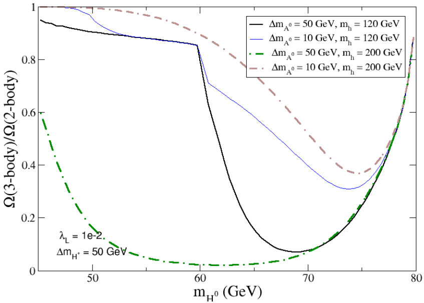


$\rightsquigarrow$ still 3-body final states significantly affect predictions for Ω_{dm}

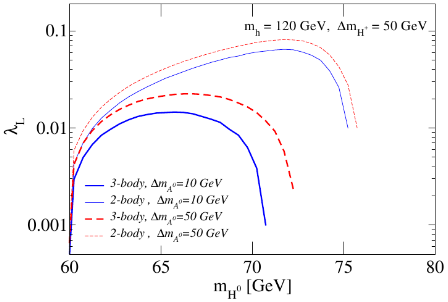
Extra contributions from 3 body annihilations

Parameters for $\Omega_{H_0} = \Omega_{dm}^{WMAP}$

Viable parameter space

Derive the $\lambda_L - m_{H^0}$ compatible with $\Omega_{dm}^{WMAP} h^2 = 0.11$

Going from 2bdy only to 2+3bdy with or without coannihilations :



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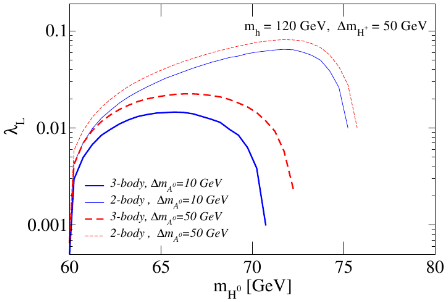

- correct $|\lambda_L|$ is reduced up to $\sim \mathcal{O}(10)$.
- $|\lambda_L| = 0$ at lower m_{H^0}
  - 2bdy settled by the onset of W^+W^- annihilations
  - 2+3bdy depends on WW^* annihilations

Viable parameter space

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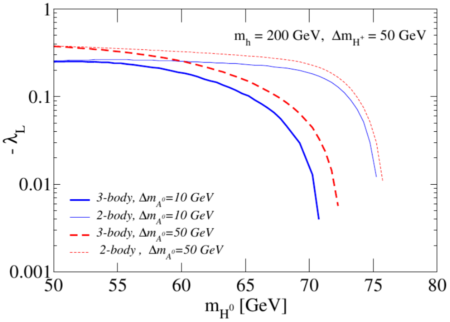

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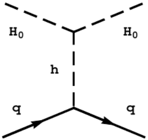
$\rightsquigarrow$ rather generic feature of the Inert doublet model independently of m_h

$\rightsquigarrow$ modify prospects for DM detection

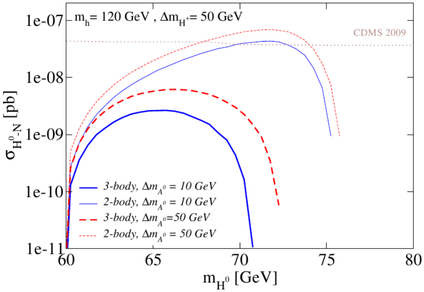
Implications for Direct Detection

Direct detection through Elastic Scattering

Prospects along the viable parameter space :



$$\sigma_{H_0-N} \propto \left(\frac{\lambda_{H_0}}{M_{H_0} M_h^2}\right)^2$$



$\rightsquigarrow$predictions for σ_{H_0-N} reduced up to $\sim \mathcal{O}(100)$

$\rightsquigarrow$ better compatibility with present bounds

Implications for Direct Detection

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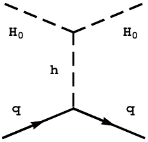

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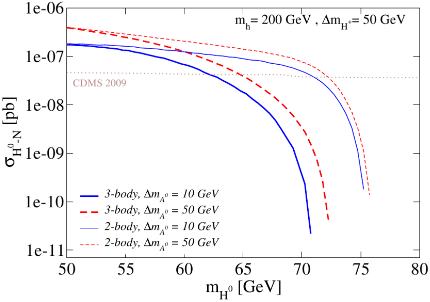

$\rightsquigarrow$ predictions for σ_{H_0-N} reduced up to $\sim \mathcal{O}(100)$

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Conclusion

The Inert Doublet is a WIMP with a rich Scalar DM phenomenology

- Viable parameter space in the
  - GeV range for $m_{H^0} \sim 130$ (160) GeV for M_h <200 GeV (600 GeV)
  - large mass gap due to efficient annihilations into $H_0 H_0 \to WW, ZZ, \bar{t}t, hh$
  - TeV range for $m_{H_0} < 530$ GeV

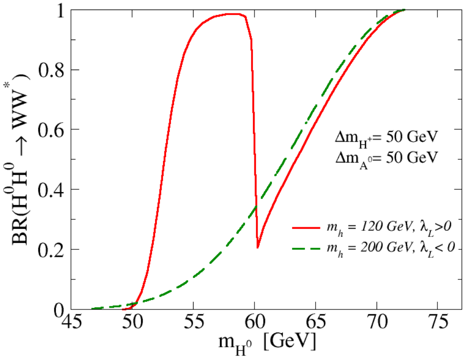
  without fine tuning with scalar and gauge (very well known ! !) interactions.

- For $m_{H_0} \lesssim m_W$, annihilation into 3 bdy final states (WW^*) MUST be taken into account
  - below W-threshold : λ_L is reduced up to $\mathcal{O}$ (10)
  - σ_{H_0-N} decreases by a factor $\mathcal{O}$ (100)
  - work in progress : new prospects for indirect detection

This is the End
Thank you for your attention ! !

Backup

For Indirect Detection including 3bdy

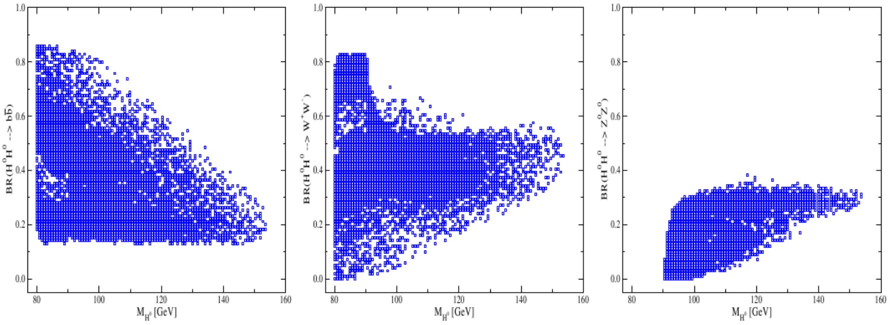


annihilations no more $\bar{b}b$ dominated

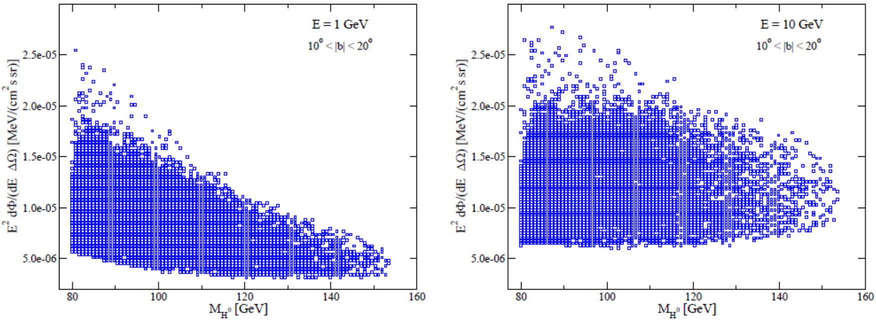
$\rightsquigarrow$BR($H_0H_0 \to WW^*$) ~ 1
for m_{H^0} near W threshold

work in progress...

Indirect Detection in the cancellation regime



Differential gamma ray flux



$\frac{d\Phi_{\rm halo}}{dE} = \frac{1}{2}\frac{\sigma v}{4\pi} r_\odot \frac{\rho_\odot^2}{m_{\rm DM}{}^2} \bar{J}\Delta\Omega \frac{dN}{dE}$, where $r_\odot = 8.5$ kpc, $\rho_\odot = 0.39\ {\rm GeV/cm^3}$ is the local Catena '09 $\bar{J}\Delta\Omega = \int_{\Delta\Omega} d\Omega(b,l) \int_{\rm los} \frac{ds}{r_\odot}\left(\frac{\rho_{{\rm halo}(r(s,\psi))}}{\rho_\odot}\right)^2$., we use NFW profile.

These fluxes are much smaller than those measured by FERMI Abdo '10 which are $\mathcal{O}(10^{-3})$ MeV/(cm^2 s sr) at those energies

It is thus not possible to obtain any constraints from this data.

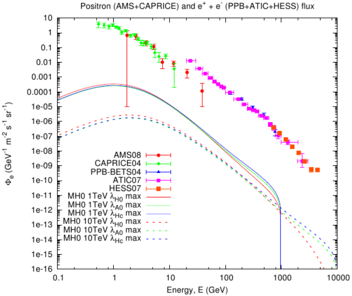
IDM large mass : Indirect detection prospects

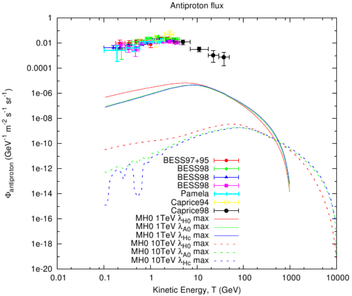
γ and ν signals : $\Phi_{\gamma,\nu}(\Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_{\rm DM}^2} N_{\gamma,\nu} \times \frac{\Delta\Omega\,\rho_0^2\,R_0}{4\pi}\,\bar{J}(\Delta\Omega)$, below the sensitivity of current experiments

Charged antimatter cosmic ray signals

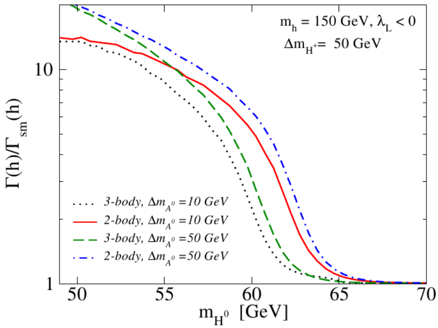
$$\vec{\nabla}\left[K(E,\vec{x})\vec{\nabla}\mathcal{N}_{\rm cr} - \vec{V}_{\rm conv}\mathcal{N}_{\rm cr}\right] + \frac{\partial}{\partial E}\left[b(E)\mathcal{N}_{\rm cr} + K_{EE}\frac{\partial}{\partial E}\mathcal{N}_{\rm cr}\right] + \Gamma(E)\mathcal{N}_{\rm cr} + \mathcal{Q}\,, = 0$$

$$\mathcal{Q} = BF\frac{\langle\sigma v\rangle\rho^2}{2m_{DM}^2} \times \sum_i \frac{dn^i_{cr}}{dE} BR_i\,.$$





$m_{H_0} < m_W$: Detection at colliders

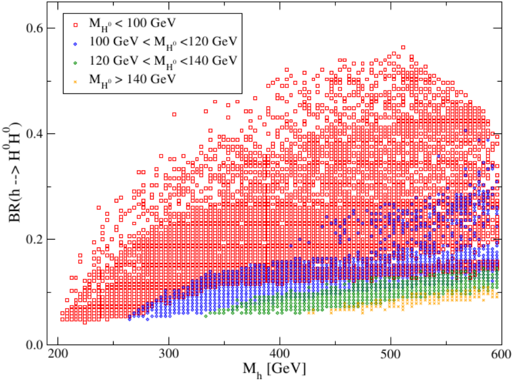


through extra contributions to $\Gamma(h)$ due to

$h \to A_0 A_0, H_0 H_0$ [Cao PRD07]

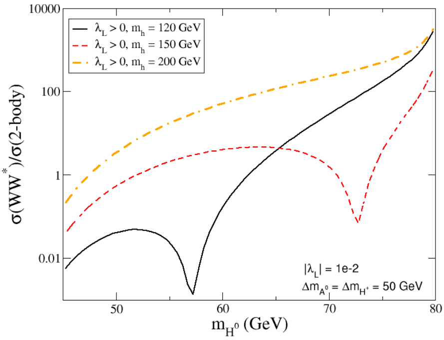
$\rightsquigarrow$ The new parameter space slightly change the prospects

Cancellations : contribution to Higgs decay width



Comparing 2-3 body annihilation cross section

3bdy annihilation dominates over 2 bdy on



- $\lambda_L = 10^{-2}$

... a significant range of the parameter space, depend on m_h

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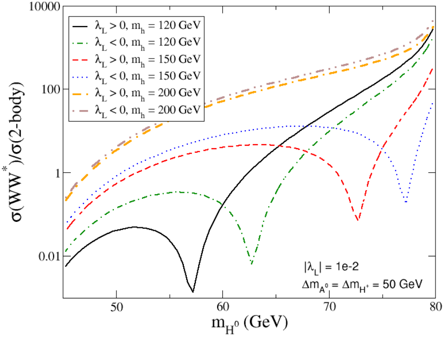

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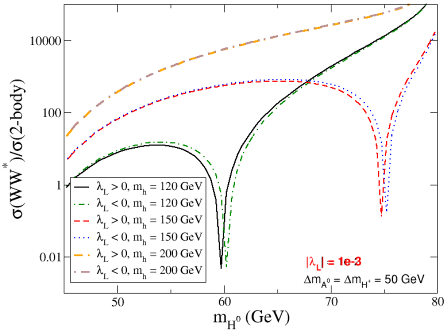


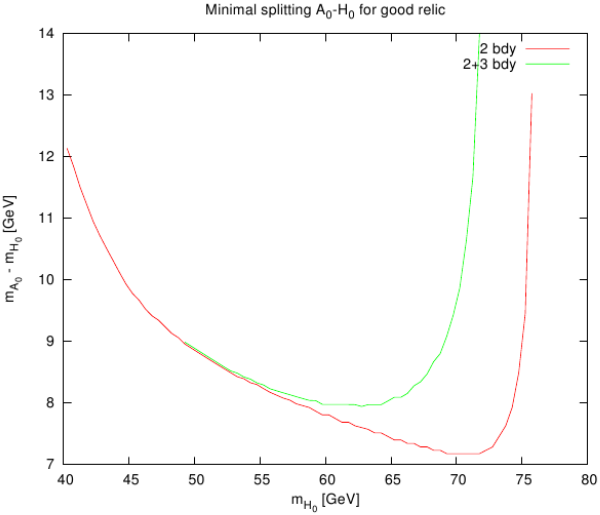
- $\lambda_L = 10^{-2}$

  ... a significant range of the parameter space, depend on m_h
- $\lambda_L = 10^{-3}$

  ... the entire mass range independently of m_h

  but not representative for $H_0 \equiv$ DM

Coannihilation



3bdy effect on DM ?

3-body processes can enhance DM annihilation :

- supersymmetric dark matter :
  - neutralino LSP : Chen & Kamionkowski JHEP '98 study $\sigma v_{v \to 0}$ and impact on ν detection from annihilation in the Earth bellow WW and $\bar{t}t$ mass threshold
    Yaguna PRD'10 demonstrate up to 10% effect on Ωh^2_χ for bino-like χ including $\bar{t}t*$ (usually 2-bdy $\bar{b}b$ dom)
  - gravitino LSP : Choi & Yaguna '1003 $W^* l$ and $Z^* \nu$ give significant (up to 90%) to $\tilde{G}$ decay (usually 2-bdy $\gamma\nu$ dom)
    Choi, Restrepo, Yaguna & Zapata '1007 gamma+antimatter signal [see Yaguna talk ! !]
- scalar DM
  - Higgs DM : Hosotani, Ko & Tanaka PLB'09 (gauge-Higgs unification) $\Omega_{DM} \rightsquigarrow m_{DM} = 75$ GeV (2bdy only) $\Rightarrow m_{DM} =$70 GeV (including 3bdy)
  - singlet scalar DM : Yaguna PRD'10, $SS \to h \to WW^*$ enhance $\sigma v_{v \to 0}$ and reduce Ω_{DM} independently of S-higgs coupling

n-uplets : Potential - constraints

- Full Potential

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

- Dark scalars couplings to Higgs and masses :

$\frac{\lambda_3}{2}\left(\frac{1}{2}\Delta^{(0)\,2} + \sum_{0<Q\leq j_n}\Delta^{(Q)}\Delta^{(-Q)}\right)(2v_0 h + h^2)$

mass of all components : $m_0^2 = \mu^2 + \frac{\lambda_3 v_0^2}{2}$

at one-loop (Cirelli'05) : $m\left(\Delta^{(Q)}\right) - m\left(\Delta^{(0)}\right) = Q^2 \Delta M_g$

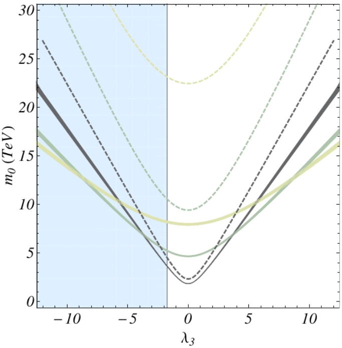
with $\Delta M_g = g M_W \sin^2\frac{\theta_W}{2} \simeq (166 \pm 1)$ MeV

- Stability constraint

$$\lambda_{1,2} > 0 ,$$
$$\lambda_3 > -\sqrt{2\lambda_1\lambda_2} .$$

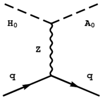
Multiplets : Relic density detection

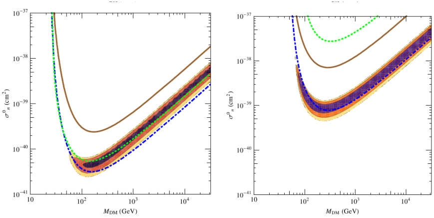
Models	$\lambda_3 = 0$	$\lambda_3 = 2\pi$	$\lambda_3 = 4\pi$	$\lambda_3 = 0$ (SE)	$\lambda_3 = 4\pi$ (SE)
Real Triplet	1.826 ± 0.028	11.1	21.9	2.3	28.1
Real Quintuplet	4.642 ± 0.072	9.6	17.4	9.4	35.7
Real Septuplet	7.935 ± 0.12	10.6	16.1	22.4	46.3

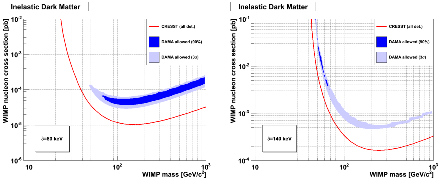


Inelastic Scattering (Arina *et* all '09) - new exclusion CRESST

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



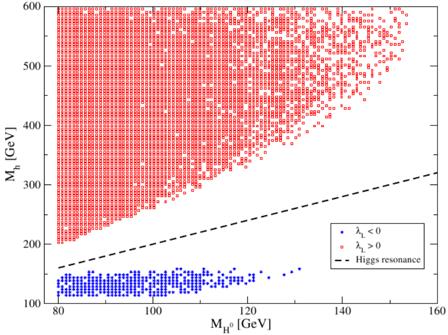


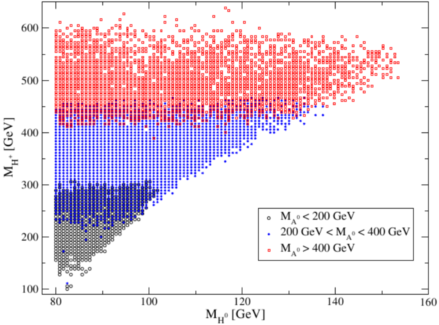


Left : allowed region consitent with DAMA @ 90, 99, 99.9 % CL for inert doublet for $\delta = 80, 150$ keV (green Xenon10, blue CRESST II 99%CL, $v_0 = 220$ km/s, $v_{esc} = 650$ km/s.

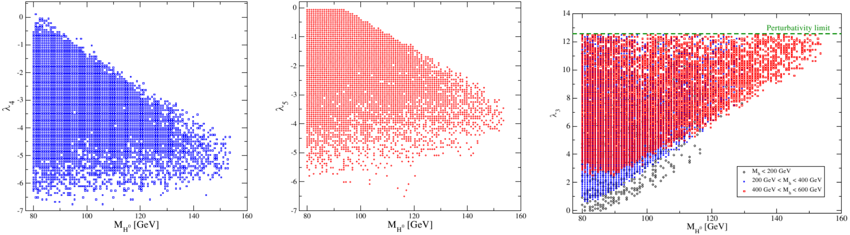
Right : new limits (july 2010 from CRESST, Seidel IDM2010), 1 pb= 10^{-36}cm^2

Cancellations require increasing M_h, m_{H^+}, m_{A_0}





Cancellations : Couplings



IDM : Mass Ranges

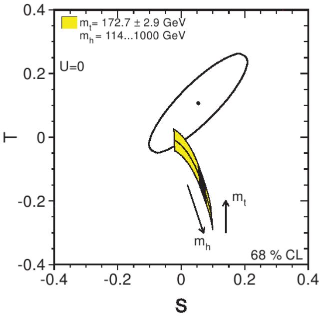
Mass Ranges	main contributions to σ_{eff}	mass splittings	main Refs
$m_{H_0} \ll m_W(\mathcal{O}(GeV))$	$H_0H_0 \to h^* \to \bar{f}f$	$\Delta m_{ij} \gtrsim m_Z - m_{H_0} \sim 90$ GeV	Andreas *et* all '08
$m_{H_0} \lesssim m_W$	$H_0H_0 \to h^* \to \bar{f}f$ $H_0A_0(H^+) \to Z^*(W^*) \to \bar{f}f^{(')}$	$\Delta m_{ij} \gtrsim m_Z - m_{H_0} \gtrsim 7$ GeV	Barbieri *et* all '06 LLH *et* all '06
$m_{H_0} \gg m_W(\mathcal{O}(TeV))$	$H_0H_0 \to ZZ, WW, hh$ coannihil into bosons	$\Delta m_{ij} \lesssim 17.6$ GeV	Hambye *et* all '09

How to conciliate Heavy Higgs and EWPT measurements ?

New physics affect EW observables

Contributions to EWPT measurement variable T from :

- Higgs : $T(M_h) = -\frac{3}{8\pi\cos^2\theta_W}\ln\frac{M_h}{M_Z}$.
- H_2 scalars : $\Delta T \approx \frac{1}{24\pi^2\alpha v^2}(M_{H^+} - M_{A_0})(M_{H^+} - M_{H_0})$



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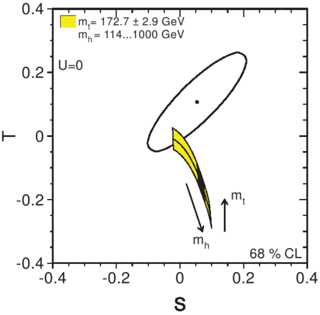


$\rightsquigarrow$ When $M_{H^+} > M_{A_0}, M_{H_0}$ positive contributions from ΔT can compensate the too large negative contributions from $T(M_h)$ due to heavy Higgs.

$\rightsquigarrow$ With H_2 new physics one may push M_h up to 500-600 GeV [Barbieri *et al* '06]

IDM : Potential - constraints

- Full Potential

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

- Dark scalars couplings to Higgs and masses :

$$\tfrac{1}{2}\left(\lambda_{H_0}H_0^2+\lambda_{A_0}A_0^2+2\lambda_{H_c}H^+H^-\right)\left(2v_0h+h^2\right)$$
$$m_h^2=2\lambda_1 v_0^2\,,\quad m_i^2=\mu_2^2+\lambda_i v_0^2.$$

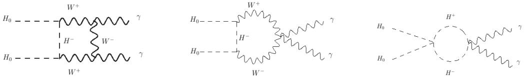
- Stability constraint

$$\lambda_{1,2} > 0\,,$$
$$\lambda_{H0}\,,\quad \lambda_{A_0}\,,\quad \lambda_{H_c} > -\sqrt{\lambda_1\lambda_2}\,.$$

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

Indirect detection : Gamma ray lines [Gustafsson *et al* '07]

Gamma Ray lines come from loop level contributions to $\Phi_\gamma^{GC} \rightsquigarrow$ negligible



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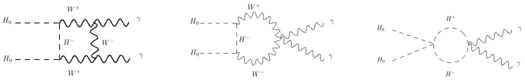

However for Heavy Higgs (low M_{H_0} only)

- Contributions from $H_0 H_0 \xrightarrow{h} f\bar{f}$ to $\langle\sigma_A v\rangle$ and Φ_γ^{GC} are suppressed
- Relic density from coannihilations

TABLE I: *IDM benchmark models. (In units of GeV.)*

Model	m_h	m_{H^0}	m_{A^0}	$m_{H^\pm}$	μ_2	$\lambda_2 \times 1$ GeV
I	500	70	76	190	120	0.1
II	500	50	58.5	170	120	0.1
III	200	70	80	120	125	0.1
IV	120	70	80	120	95	0.1

TABLE II: *IDM benchmark model results.*

Model	$v\sigma_{tot}^{v\to 0}$	Branching ratios [%]:					$\Omega_{\rm DM}h^2$
	[cm^{3}s^{-1}]	$\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	
I	1.6×10^{-28}	36	33	26	2	3	0.10
II	8.2×10^{-29}	29	0.6	60	4	7	0.10
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IV	1.9×10^{-26}	0.04	0.1	85	5	10	0.11

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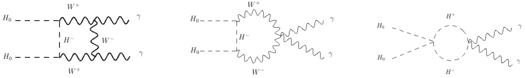

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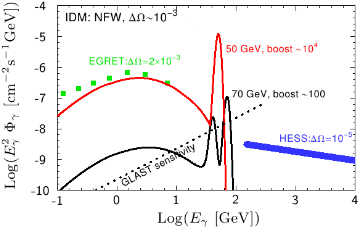
- Contributions from $H_0 H_0 \xrightarrow{h} f\bar{f}$ to $\langle \sigma_A v \rangle$ and Φ_γ^{GC} are suppressed
- Relic density from coannihilations
- Gamma line signal can become the main feature of the gamma ray spectrum



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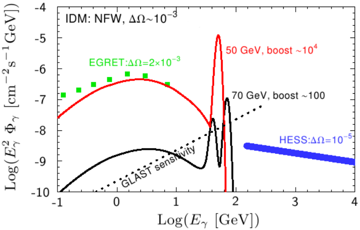
Problem : For significant gamma ray lines need large boost factors



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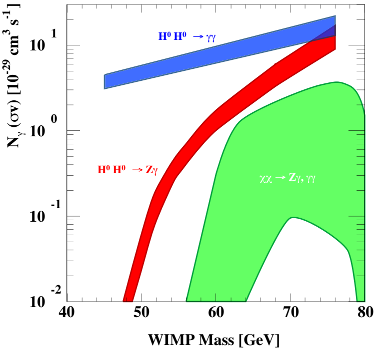
General feature : stronger line signals in the IDM than in the MSSM

Annihilation rate into γ lines



$M_h = 500$ GeV, $M_{H^\pm} = M_{H_0} + 120$ GeV, $\lambda_2 = 0.1$

Constraints from LEPII Lundstrom, Gustafsson & Edsjo PRD '09

Exclusion plot from LEPII analysis derived from on neutralino searches :

$$e^+e^- \to \chi_1^0\chi_2^0 \to \chi_1^0\chi_1^0 f\bar{f}$$

to be compared with :

$$e^+e^- \to A^0H^0 \to H^0H^0 f\bar{f}$$

taking into account different spin and different decay processes for the NLSP