Direct Detection & Inert Multiplet Dark Matter

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Workshop on Multi-Higgs Models, September 2009, Lisboa, Portugal,

T. Hambye, FSL, L. Lopez-Honorez, J. Rocher, arXiv:0903.4010
C. Arina, FSL, M. Tytgat, arXiv:0907.0430
FSL, E. Nezri, E. Athanassoula, R. Teyssier, arXiv:0909.2028

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PHYS

Motivations

DAMA signal @ 8.2 σ C.L.

Null Experiments

Analysis of the compatibility in simple
Scalar extensions of the Standard Model

DM candidate : scalar particle

in two possible scenarios

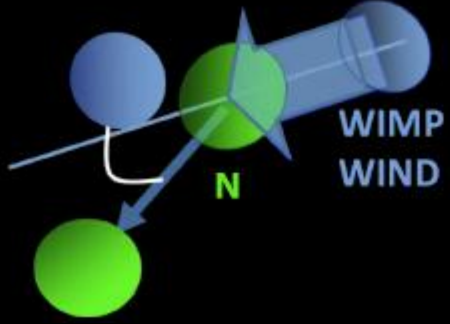
Elastic Scattering

Light WIMP : $M_{DM} \sim O(10)$ GeV

Inelastic Scattering

Heavy WIMP : $M_{DM} \sim O(1\text{-}10)$ TeV

Direct Detection – Event rate



Differential rate

$$\frac{dR}{dE_R} = \frac{\rho_{DM}}{M_{DM}} \frac{d\sigma}{dE_R} \eta(E_R, t)$$

particle and nuclear physics

$$\frac{d\sigma}{dE_R} = \frac{M_N}{2\mu_n^2} \sigma_n^0 \frac{\left(f_p^2 Z + (A-Z) f_n^2\right)^2}{f_n^2} F^2(E_R)$$

astrophysics

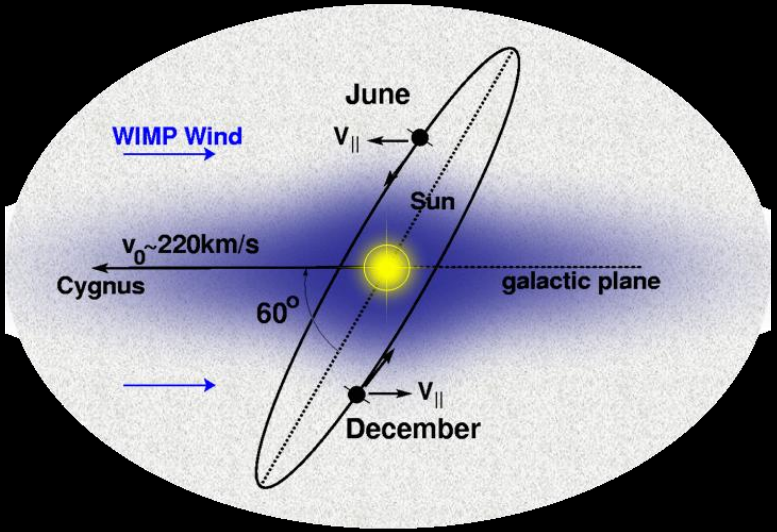
$$\eta = \int d^3\vec{v} \frac{1}{\left|\vec{v} - \vec{v}_{\oplus,G}\right|}$$

Total rate

$$R(t) = \int_{E_1}^{E_2} dE_R \, \varepsilon(E_R) \left(\frac{dR}{dE_R} * G(E_R, \sigma(E_R)) \right)$$

detector efficiency and energy resolution

Annual modulation



Modulation of the Earth velocity

$$v_{\oplus,G} = v_S + v_{\oplus,S} \sin \gamma \cos \omega(t - t_0)$$

$$t_0 = t_1 + \frac{\pi}{2\omega} + \frac{1}{\omega} \arctan \frac{\vec{v}_S \cdot \vec{e}_2}{\vec{v}_S \cdot \vec{e}_1} \approx 151.5$$

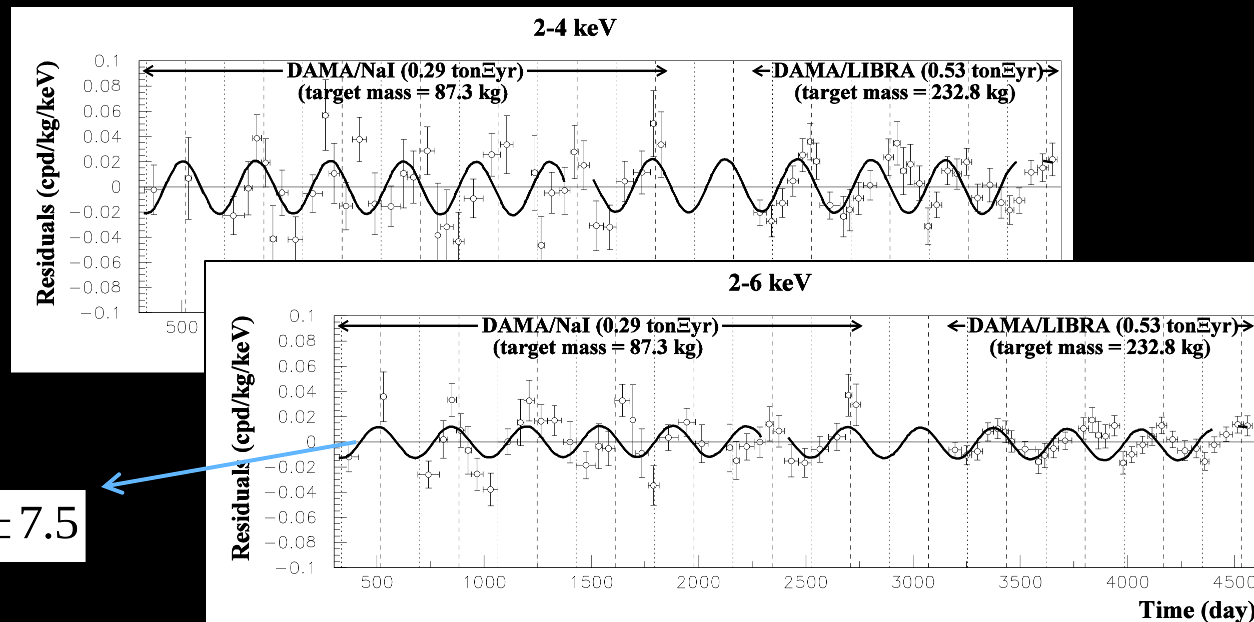
Modulation of the differential event rate

$$\eta(E_R, t) = \eta_0(E_R) + \eta_1(E_R) \frac{v_{\oplus,S}}{v_S} \sin \gamma \cos \omega(t - t_0)$$

DAMA signal

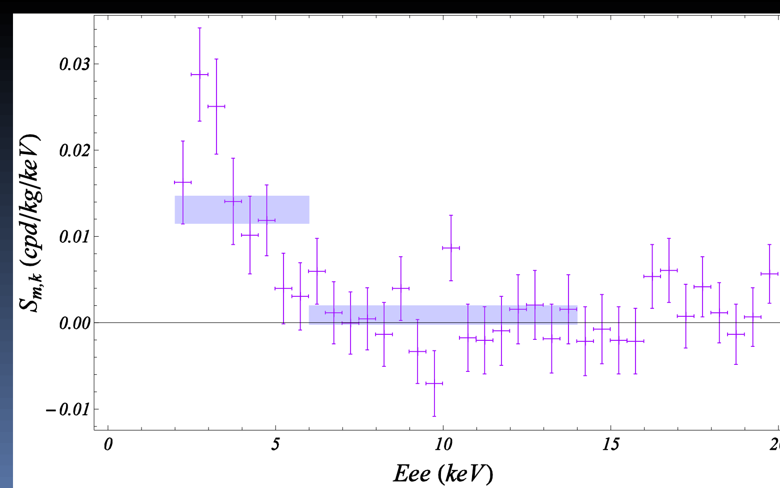
Eur. Phys. J. C56: 333-355(2008) arXiv:0804.2741

Time residuals



$$t_0 = 144.0 \pm 7.5$$

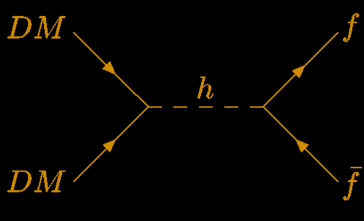
Modulation spectrum

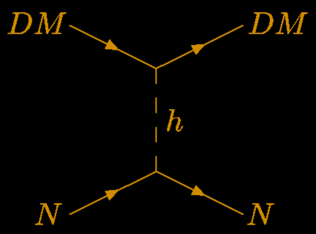


A simple scenario

CP. Burgess, M. Pospelov, T. ter Veldhuis, Nucl. Phys. B619:709 (2001) arXiv:hep-ph/0011335
S. Andreas, T. Hambye, MHG. Tytgat, JCAP 0810:034(2008) arXiv:0808.0255

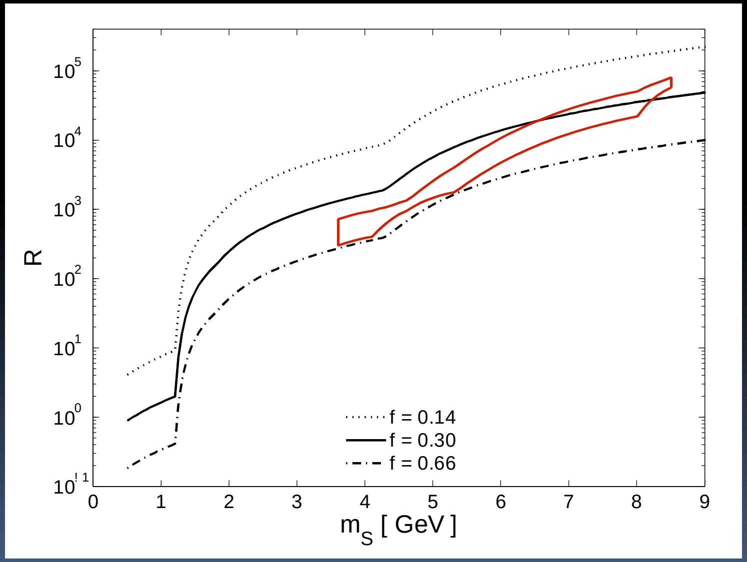
DM is a Singlet Scalar coupled to SM through Higgs



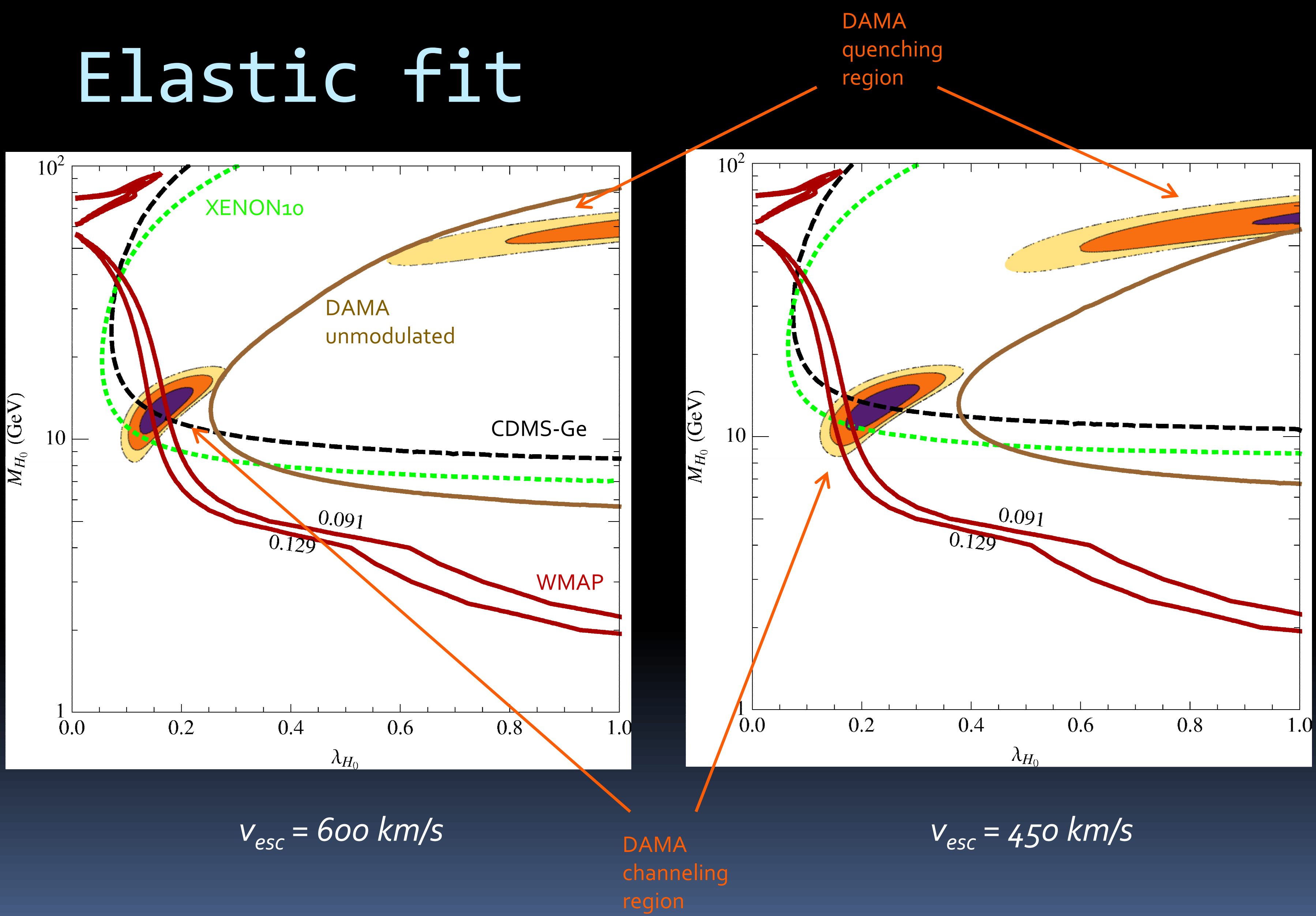


- Scalar field, odd under Z_2 parity
- Standard freeze-out in thermal bath
- Spin-independent
- 2 parameters :

DM mass M_{DM}
Scalar coupling λ



Elastic fit



v_{esc} = 600 km/s

v_{esc} = 450 km/s

Uncertainties

Nuclear physics

- Form factor (Helm) 10-20%

$$F(q) = 3e^{-q^2 s^2/2} \frac{J_1(qr)}{qr}$$

- Effective coupling to nucleon

$$f = 0.3 \qquad 0.15 \le f \le 0.6$$

- Quenching factors, channeling effects

$$q_I = 0.09 \qquad q_I \approx 1$$

(R. Bernabei et al., Eur.Phys. J., C53:205213 (2008), arXiv:0710.288)

Astrophysics

- Local DM density

$$\rho_{DM} = 0.3\ GeV / cm^3$$

- Velocity distribution: isotropic M-B

$$\mathrm{f}(\vec{v}) \propto e^{-v^2/v_0^2}$$

- Escape velocity
- Anisotropies ??
- Deviations from M-B ??
- Clumps ??
- Rotating Dark Disk component ??

Summary I

- A singlet scalar DM candidate enables to have both the correct relic density and a fit of DAMA.

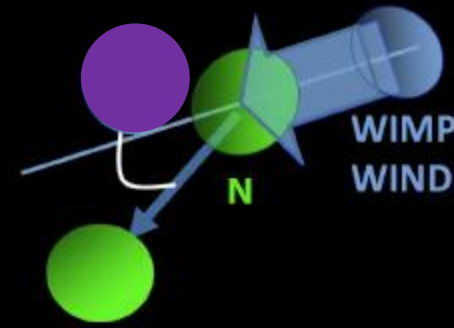
- The channeling region of DAMA is only marginally consistent with null experiments, but some freedom is permitted by nuclear and astrophysical uncertainties.

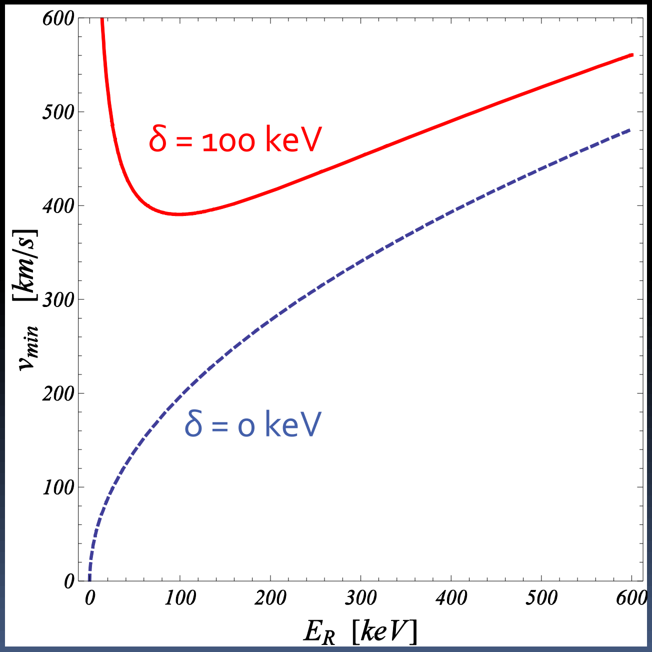
Can we do better ?

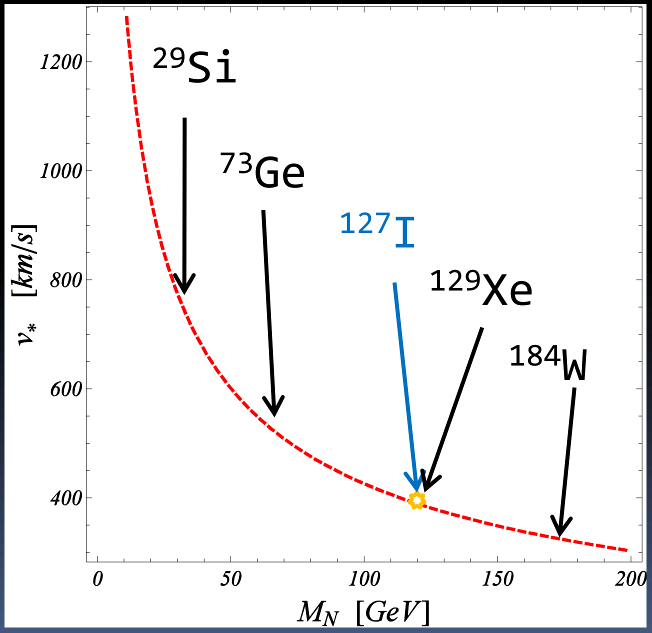
Inelastic Dark Matter

D. Tucker-Smith and N. Weiner, Phys. Rev. D64, 043502(2001), arXiv:hep-ph/0101138.

$$v_{\min} = \frac{1}{\sqrt{2M_N E_R}}\left(\frac{M_N E_R}{\mu} + \delta\right)$$

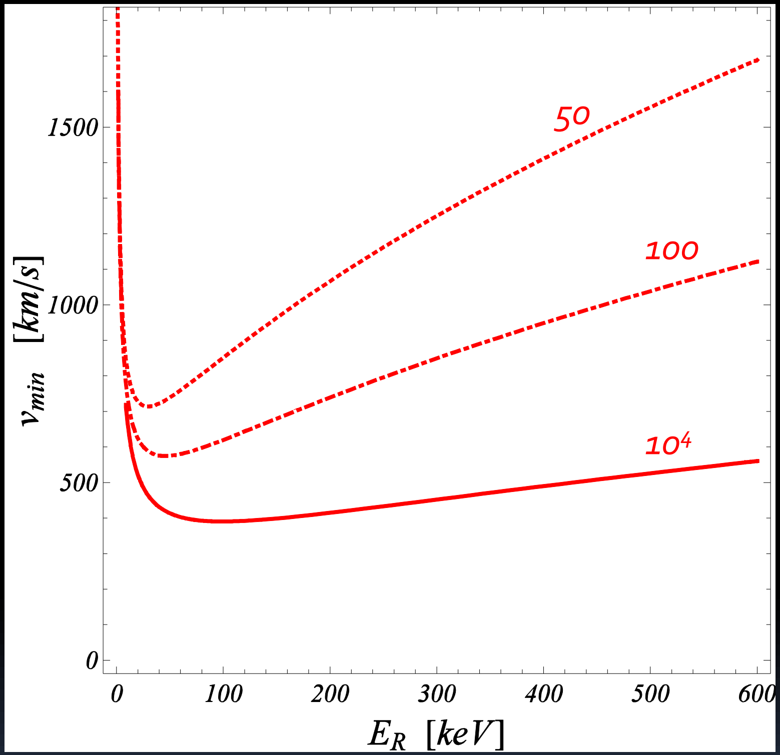


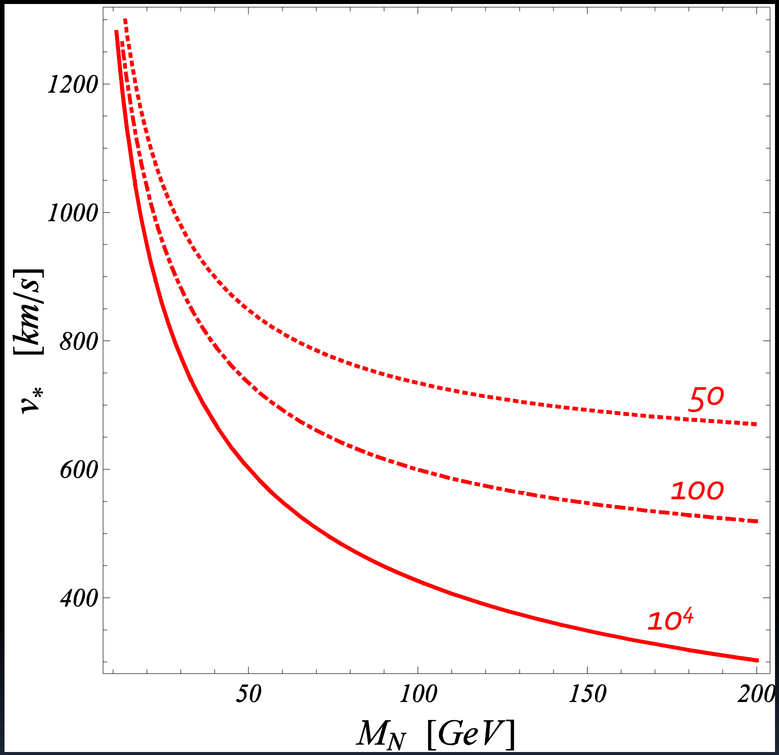




M_{DM} = 10 TeV

M_{DM} = 50 Gev, 100 GeV, 10 TeV





Q: Can we realize the Inelastic scenario with scalar DM ?

A: Yes, the simplest possibility is to take an Inert Scalar Doublet

Inert Doublet Model

Deshpande & Ma '78

- Minimal extension of the Standard Model:

  usual Higgs doublet H_1 + additional inert doublet H_2 , odd under Z_2

- Z2 symmetry → If lightest odd particle is neutral → candidate for DM

  → no FCNC

- Langrangian and Potential

Gauge interactions

$$L = (D_\mu H_2)^+ (D^\mu H_2) - V(H_1, H_2)$$

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

Scalar interactions

- $\langle H_2 \rangle = 0$: Z_2 unbroken

- Mass spectrum at tree level

$$H_1 = \begin{pmatrix} 0 \\ (v_0 + h)/\sqrt{2} \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_+ \\ (H_0 + iA_0)/\sqrt{2} \end{pmatrix}$$

$Y_{H2} = 1$

DM candidate

$$M_{H_0}^2 = \mu_2^2 + \lambda_{H_0} v_0^2$$
$$M_{A_0}^2 = \mu_2^2 + \lambda_{A_0} v_0^2$$
$$M_{H_c}^2 = \mu_2^2 + \lambda_{H_c} v_0^2$$

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

- Quartic Scalar interactions with Higgs

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

- If $\lambda_5 = 0$, there is a Peccei-Quinn symmetry

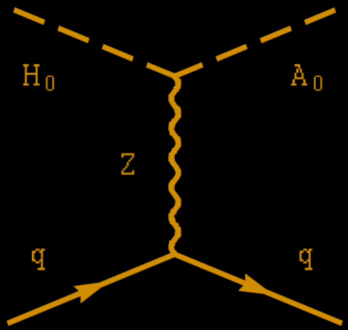
  → $\delta = M_{Ao} - M_{Ho}$ is protected against radiative corrections

- Perturbativity & Vacuum stability conditions

  Low mass regime >< High mass regime

Direct detection ?

- At tree level :

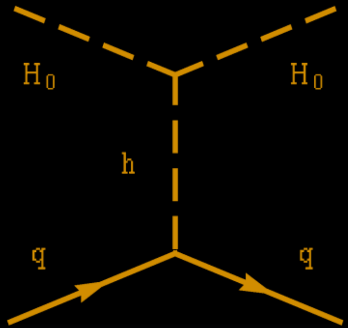


× $\delta = 0$:

Excluded by null experiments

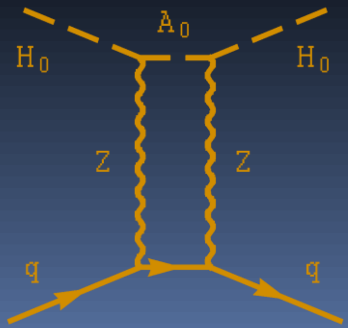
√ $\delta \sim 100$ *keV* :

Inelastic DM



Subdominant if *Z* exchange present

- At 1-loop level :

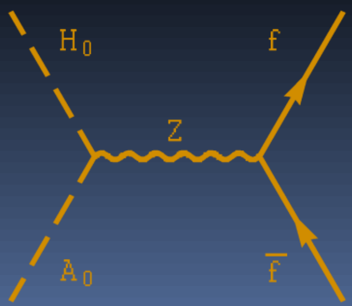


Minimal Elastic cross section

→ IDM can be tested by future DD experiments

Low mass regime & DAMA

- Either $M_{Ao}, M_{Hc} >> M_{Ho} \sim 10\,GeV$, A_o, H_c decouple → back to singlet
    - √ Z width constraint
    - √ Relic abundance set by WMAP
- Either $\delta = M_{Ao} - M_{Ho} \sim 100\,keV$ & $M_{Hc} > M_{Ho}$
    - √ Z width constraint → OK if $M_Z < 2\,M_{Ho}$
    - × Relic abundance set by WMAP : too fast coannihilation



Asymmetry ?

High mass regime & DAMA

- Annihilation into pairs of gauge bosons open

  → Mass threshold set by WMAP $M_{H_0} \geq 535\ GeV$

- Small mass splittings → coannihilations non negligible

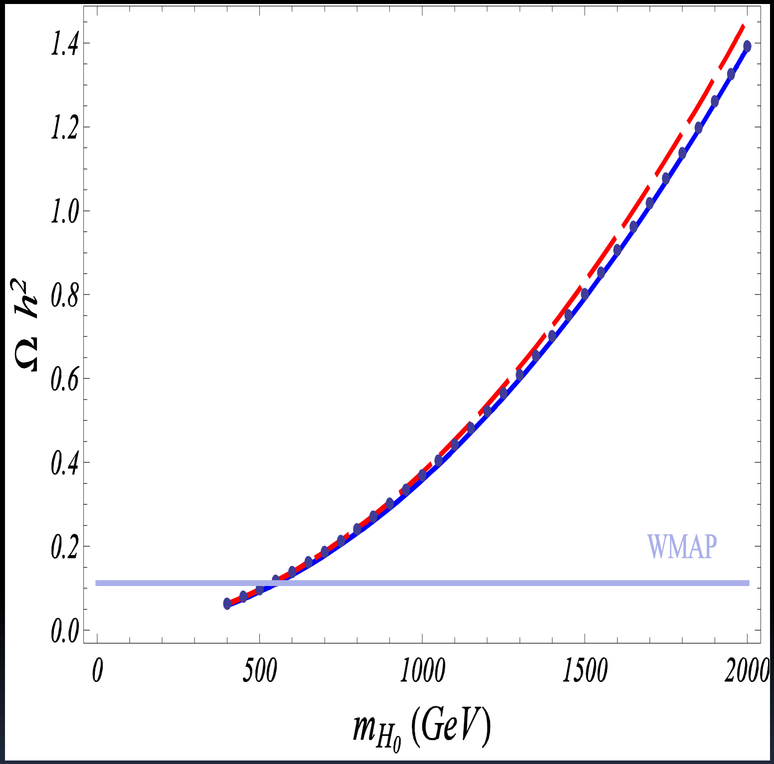
- Three independent scalar quartic couplings $\lambda_{Ho}, \lambda_{Ao}, \lambda_{Hc}$

  √ $\delta = M_{Ao} - M_{Ho} \sim 100\ keV$

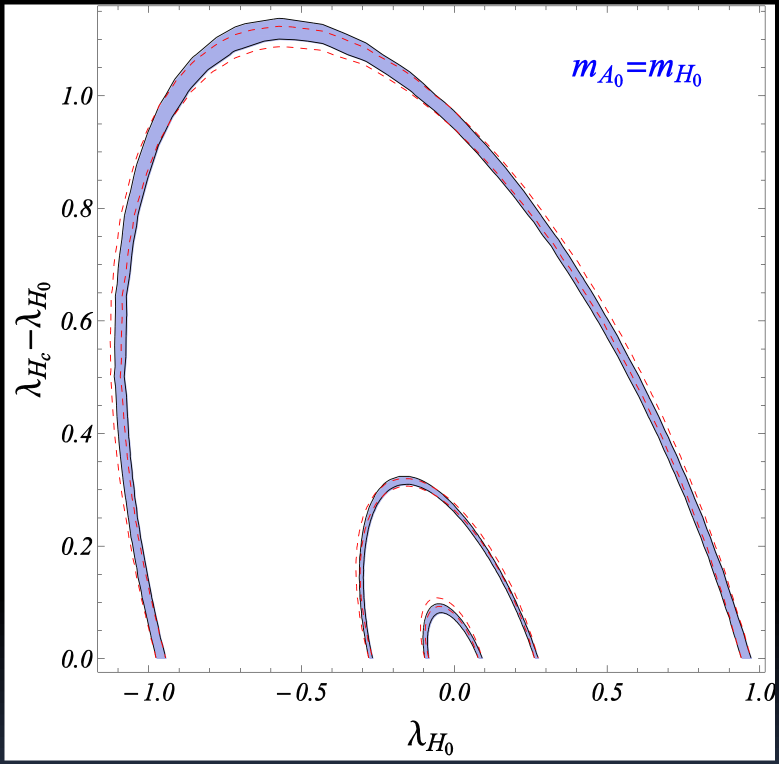
$$\lambda_5 = 3.3 \cdot 10^{-7} \left(\frac{M_{H_0}}{100\ GeV} \right) \left(\frac{\delta}{100\ keV} \right)$$

  √ Relic abundance set by WMAP

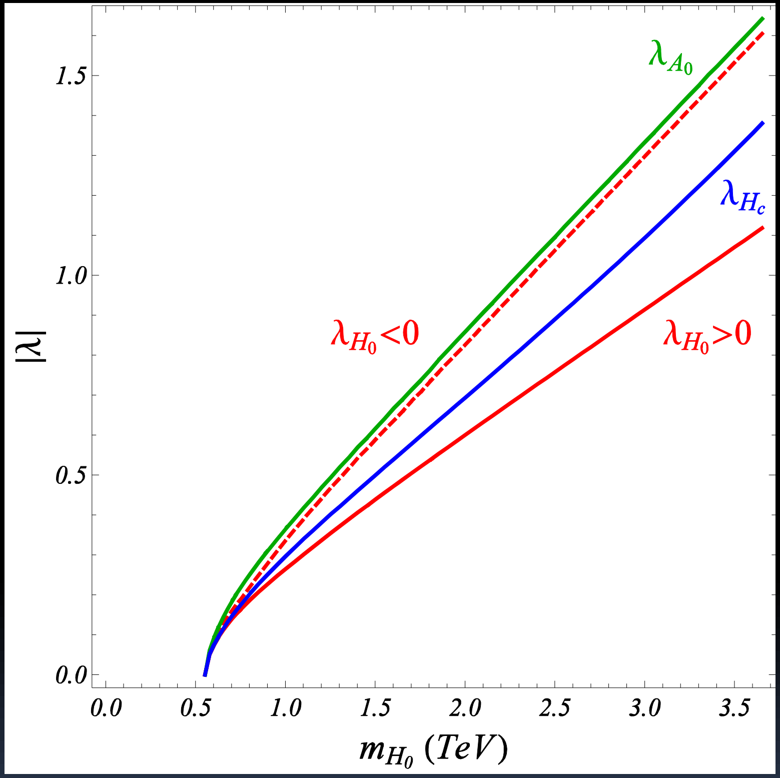
Pure gauge limit



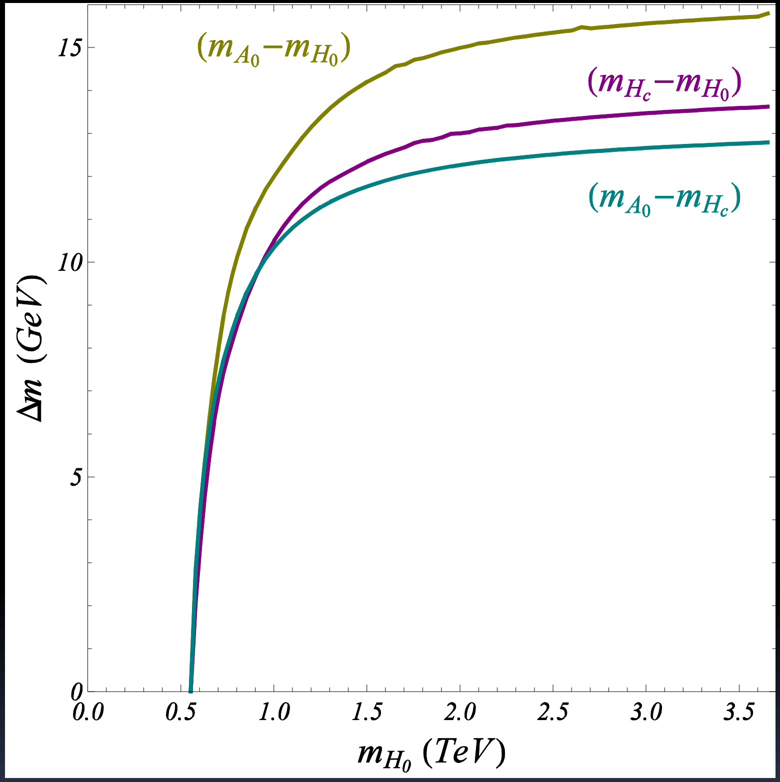
With scalar quartic couplings



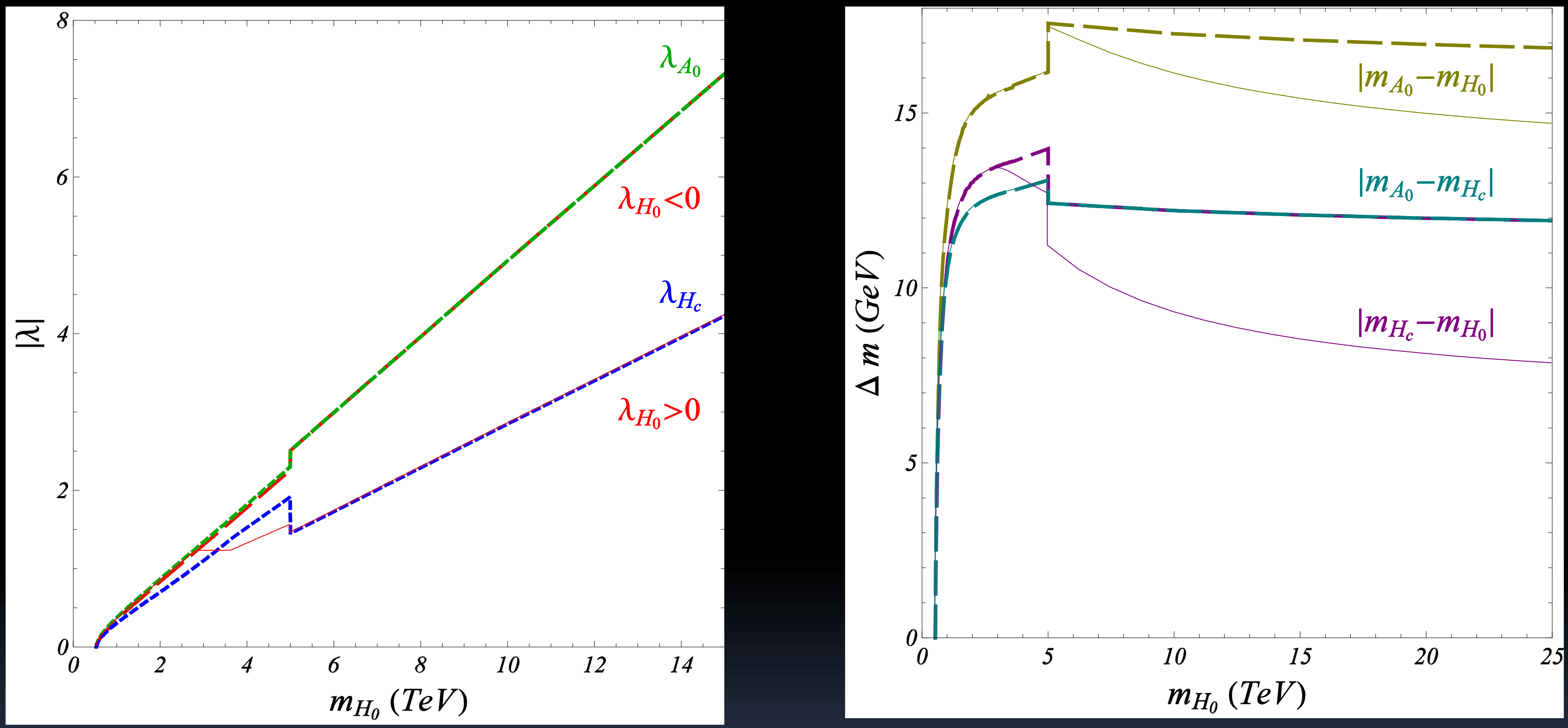
Scalar quartic couplings



Mass splitting

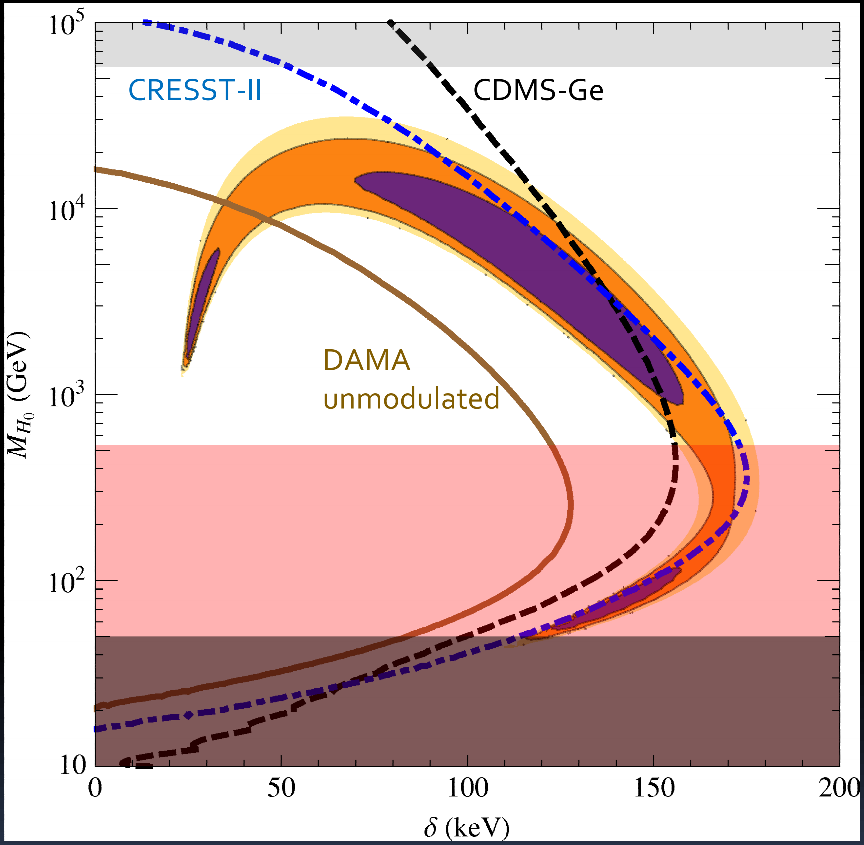


If we try to take EW phase transition and
vacuum stability conditions into account .....

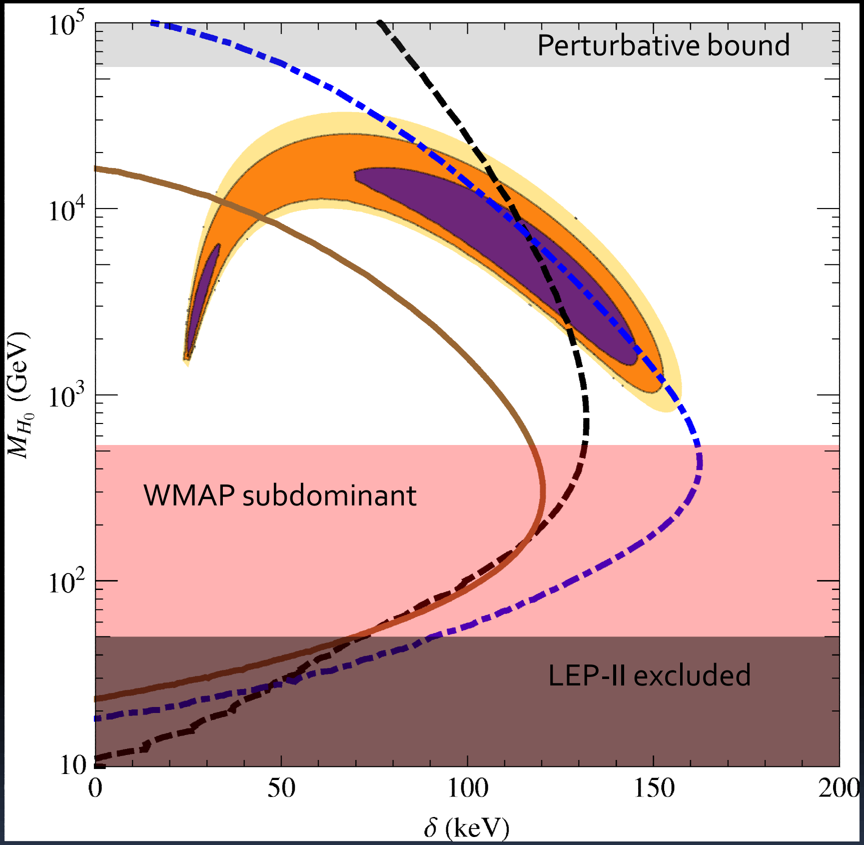


So what do we get ?

Inelastic fit



v_{esc} = 650 km/s



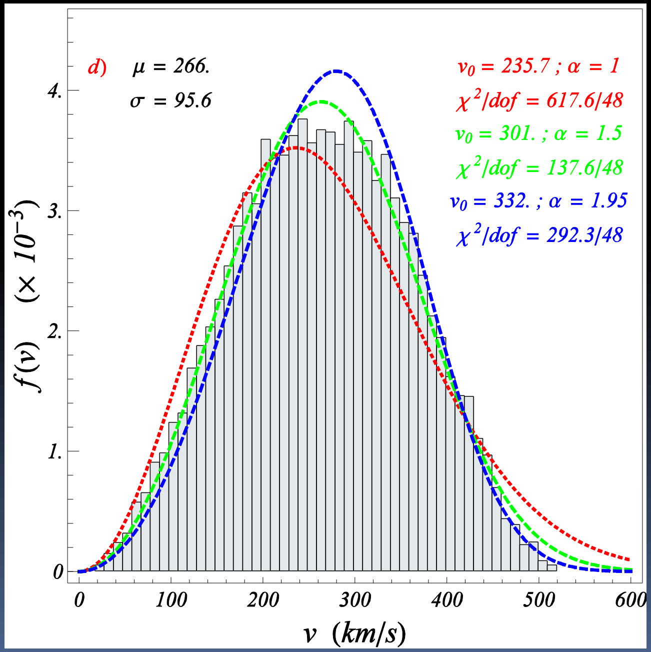
v_{esc} = 450 km/s

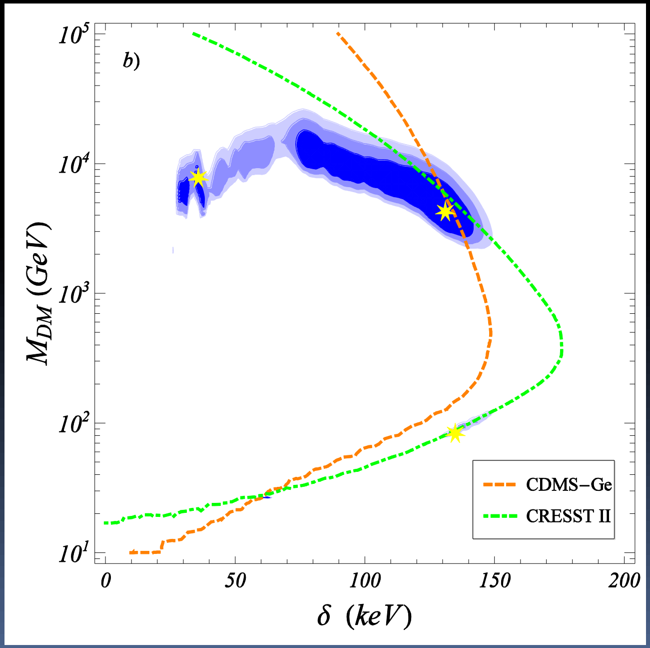
Candidates for iDM

- $M_{DM} \sim few\,TeV,\ \delta \sim 30\ keV$ → Excluded by DAMA itself
- $M_{DM} \sim few\,TeV,\ \delta \sim 130\ keV$

→ Improved goodness-of-fit with a realistic halo

Here : fit with the DM halo from a N-body simulation with stars and gas





- M_{DM} ~ 50-100 GeV , δ ~ 130 keV
  1. Subdominant relic density
  2. Charge asymmetry

$$\lambda_5 = 3.3 \cdot 10^{-7} \left(\frac{M_{H_0}}{100\ GeV} \right) \left(\frac{\delta}{100\ keV} \right)$$

In the limit $\lambda_5 \to 0$, exact PQ symmetry

$$H_n = (H_0 + iA_0)/\sqrt{2}$$

PQ = +1

Charge asymmetry only broken by processes controlled by λ_5

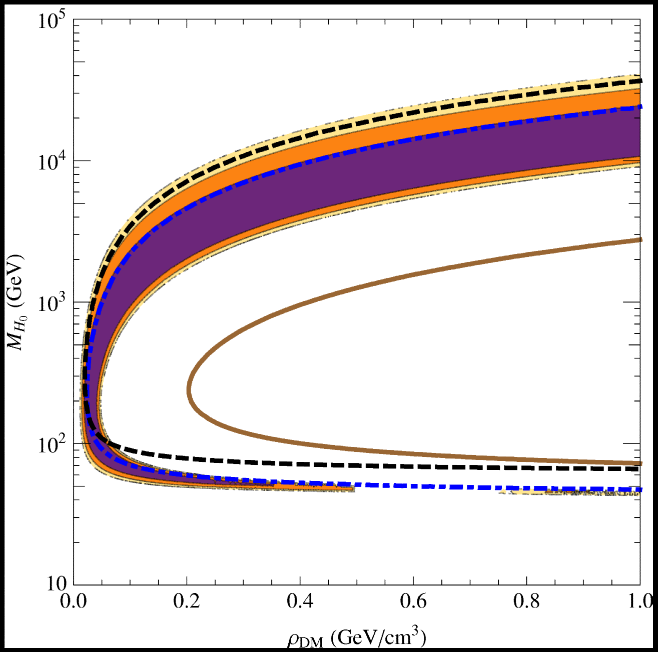
$$H_n\ H_n \to (h) \to f\ \bar{f}$$
$$H_n\ H_n \to h\ h$$
$$H_n\ h \to H_n^*\ h$$

Annihilation through Higgs neglected

Simplified Boltzmann equation to get an upper bound. We find

$$\lambda_5 < 10^{-7}\, g_*^{1/4} \sqrt{\frac{T}{10\ GeV}}$$

→ out-of equilibrium for $M_{DM} < O(100)$ GeV



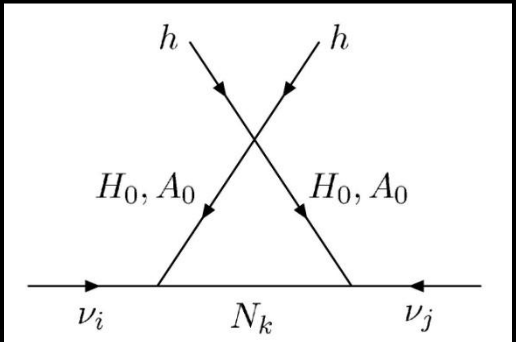
Neutrino masses & Leptogenesis

- Add right-handed neutrinos. If they are odd under Z_2 , the most general lagrangian is

$$L = L_{IDM} + i\overline{N}_i \partial N_i - \overline{N}_i Y_{Nij} \widetilde{H}_2^+ L_j - \frac{1}{2} m_{Ni} N_i N_i$$

- Radiative see-saw neutrino masses

$$(m_\nu)_{ij} = -\frac{\lambda_5 v_0^2}{16\pi^2} \sum_k \frac{Y_{Nki} Y_{Nkj}}{m_{Nk}} \left[\log \frac{m_{H_0}^2}{m_{Nk}^2} + 1 \right]$$



Compare with standard see-saw

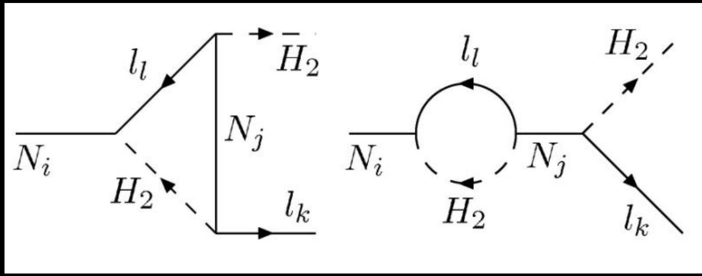
$$(m_\nu)_{ij} = -\frac{v_0^2}{2} \sum_k \frac{Y_{Nki} Y_{Nkj}}{m_{Nk}}$$

Extra suppression allows for lower right-handed neutrino masses

- Leptogenesis

  CP asymmetry essentially unchanged

$$\varepsilon_{N1} = -\sum_{j=2,3} \frac{3}{16\pi} \frac{m_{N1}}{m_{Nj}} \frac{\sum_i \mathrm{Im}\left[\left(Y_{N1i} Y^{+}_{Nij}\right)^2\right]}{\sum_i \left|Y_{N1i}\right|^2}$$



$$m_{N1} \geq \frac{\lambda_5}{8\pi^2} 6\cdot 10^8 \ GeV$$

$$\lambda_5 \leq 1.5\cdot 10^{-4} \left(\frac{m_{N1}}{1\,TeV}\right)$$

→ Bound on N_1 mass lowered to TeV scale !

- Yukawa couplings

  Out-of-equilibrium decay of N_1 →

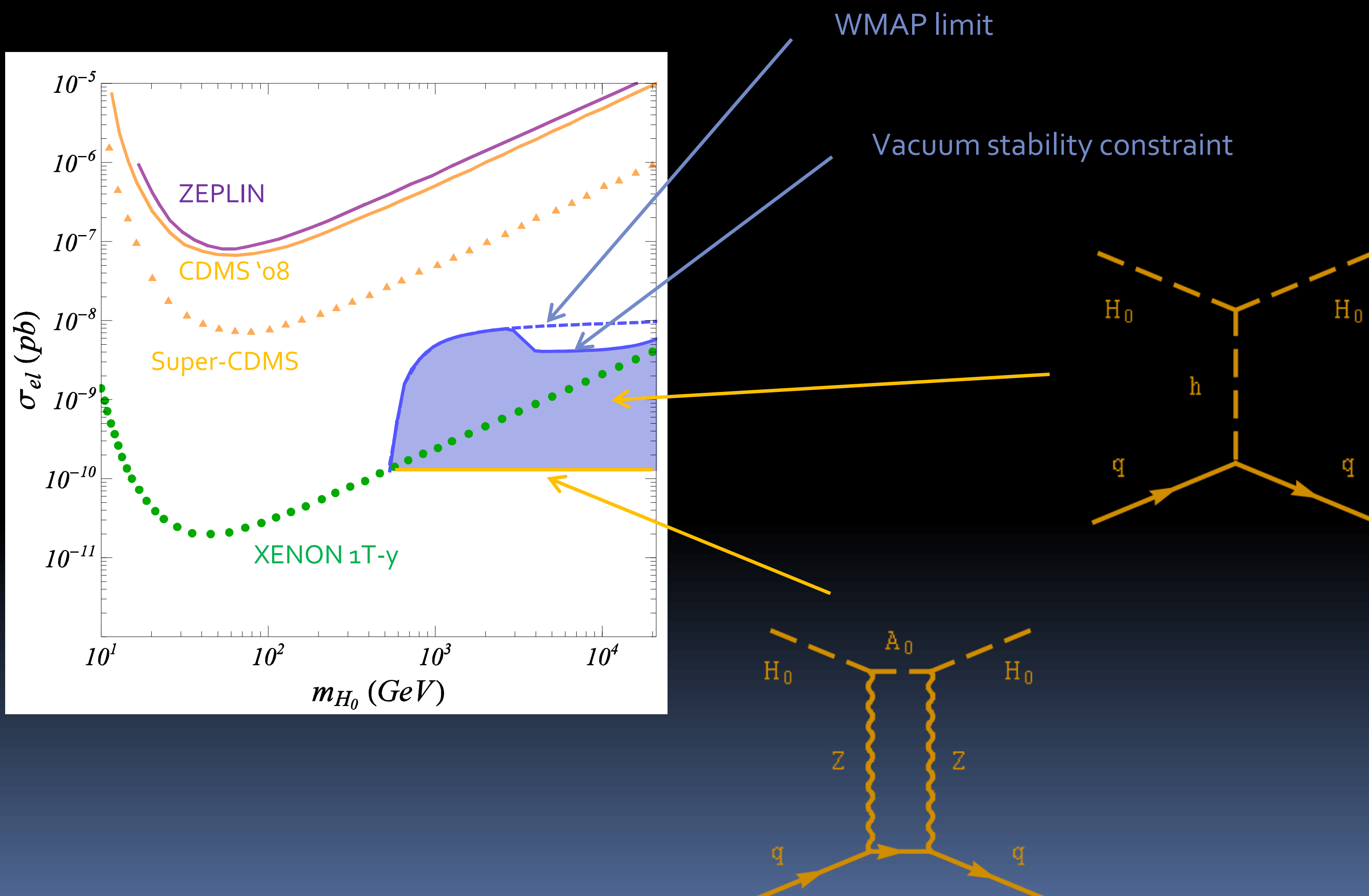
$$\left|Y_{N1j}\right|^2 < 4\cdot 10^{-14} \left(\frac{m_{N1}}{1\,TeV}\right)$$

  Hierarchical pattern to obtain observed neutrino Δm^2 →

$$Y_{Nji} \geq 1\cdot 10^{-3} \left(\frac{m_{Nj}}{m_{N1}}\right)^{1/2} \qquad (j = 2 \ or \ 3)$$

- Washout conditions OK!

If $\delta >> 100$ keV ...



Summary II

- The Inert Doublet Model naturally provides candidates for inelastic DM.
- Heavy candidates with a mass M_{DM} ~ *few TeV* are consistent with WMAP.
  A simple extension with odd right-handed neutrinos at the TeV scale
  enables to generate radiative neutrino masses & leptogenesis at the TeV scale.
- Lighter candidates with a mass M_{DM} ~ *50-100 GeV* have a subdominant
  relic abundance, unless protected by an asymmetry in the Dark sector.
- If *Z* exchange is negligible, scalar interations will hopefully be probed by
  future ton-sized direct detection experiments.

Higher Multiplets

Renormalizable level

- Potential

$$V = V_1(H_1) + \mu^2 |H_n|^2 + \frac{\lambda_2}{2} |H_n|^4 + \lambda_3 |H_1|^2 |H_n|^2 + \frac{\lambda_4}{2} \left(H_n^+ \tau_a^{(n)} H_n \right)^2 + \lambda_5 \left(H_1^+ \tau_a^{(2)} H_1 \right) \left(H_n^+ \tau_a^{(n)} H_n \right)$$

H_n is a *$SU(2)_L$* multiplet of dimension *n*

Common mass

Mass splitting between components with different electric charge

Unlike the doublet case, no mass splitting between real and imaginary parts of neutral field

- Direct detection constraints → only multiplets with *Y = 0* are allowed → *n* is odd

1. Complex multiplet : λ_5 small to have DM
   → Very similar to the real multiplet case except for the doubling of number of fields

$$\lambda_5 \leq 2.2 \cdot 10^{-2} \left(\frac{m_0}{1\,TeV} \right)$$

2. Real multiplet : last two terms of potential vanish identically

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

Mass spectrum
$$m_0^2 = \mu^2 + \frac{1}{2}\lambda_3 v_0^2$$

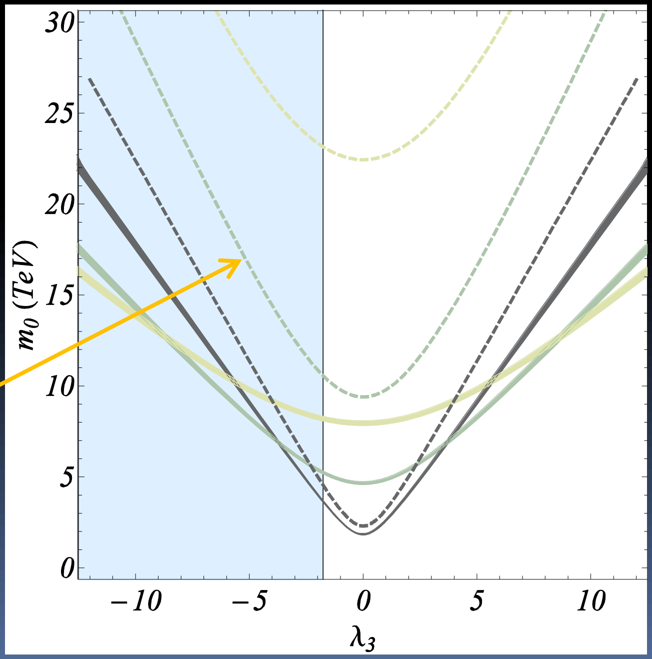
$$H_n = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^{(Q)} \\ \cdots \\ \Delta^{(0)} \\ \cdots \\ \Delta^{(-Q)} \end{pmatrix}$$

Quartic Scalar interactions with Higgs
$$V_{H-h} = \frac{\lambda_3}{2} \left(\frac{1}{2} \Delta^{(0)2} + \sum_{Q>0} \Delta^{(Q)} \Delta^{(-Q)} \right) \left(2 v_0 h + h^2 \right)$$

Annihilation cross section & relic density

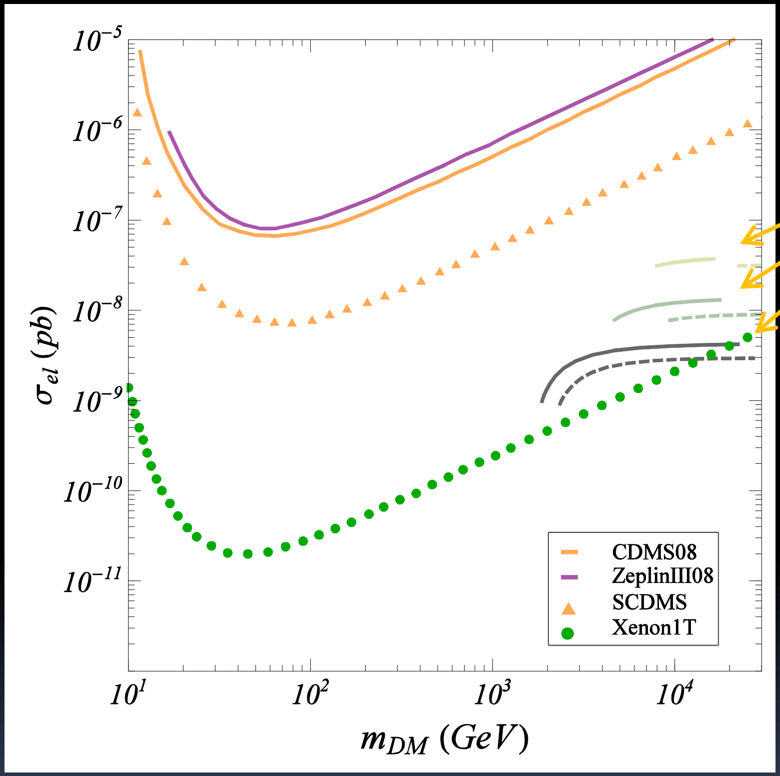
$$\sigma_0^{(n)} v = \frac{(n^2-1)(n^2-3)}{n} \frac{g^4}{128\pi \, m_0^2}$$

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



Sommerfeld effects important for higher multiplet models !!

Direct detection : n = 3, 5, 7



Direct detection rate determined by WMAP !!

→ Testable models !

Beyond the renormalizable level

- If we can generate a mass splitting δ between the real and the imaginary parts of the neutral field, models with Y ≠ 0 could be salvaged.
- Example for $n = 3$ → dimension 6 operator

$$V_6 = \frac{\lambda_6}{\Lambda^2}\left[\left((H_1^+ \tau_a^{(n)} \tilde{H}_1)\Delta_a\right)^2 + h.c.\right]$$

$$\Delta = \begin{pmatrix} \Delta_{++} \\ \Delta_+ \\ \Delta_0 \end{pmatrix}$$

$$\delta = 2\lambda_6 \frac{(v_0/\sqrt{2})^4}{m_0 \Lambda^2}$$

Conjugate multiplet of H_1

$\lambda_6 \sim 10^{-2}$, $m_0 \sim 2\,TeV$, $\Lambda \sim 10\,TeV$ → $\delta \sim 100\,keV$

- In general :

$$\delta = 2\lambda_6 \frac{(v_0/\sqrt{2})^{2(n-1)}}{m_0 \Lambda^{2(n-2)}}$$

→ With reasonable assumptions, for $n>3$, δ is too small for the inelastic DM scenario

Summary III

- Higher Multiplet models cannot fit DAMA at the renormalizabe level.

- Real multiplets with $n = 3, 5, 7$ provide viable DM candidates with a direct detection cross section testable in future ton-sized experiments.

- Dimension > 4 operators enable to generate a mass splitting between the real and the imaginary parts of the neutral component in higher multiplet models. Only the case $n = 3$, $Y = 2$ is viable with realistic assumptions.