The real singlet scalar dark matter model

Wan-Lei Guo and Yue-Liang Wu, JHEP10(2010)083
Wan-Lei Guo, Yue-Liang Wu, Yu-Feng Zhou, PRD82:095004,2010
Wan-Lei Guo and Yue-Liang Wu, in preparation

1. Real singlet scalar DM model
2. Gauge singlet DM in the LR model
3. Neutrino signals in Super-K and IceCube

郭万磊

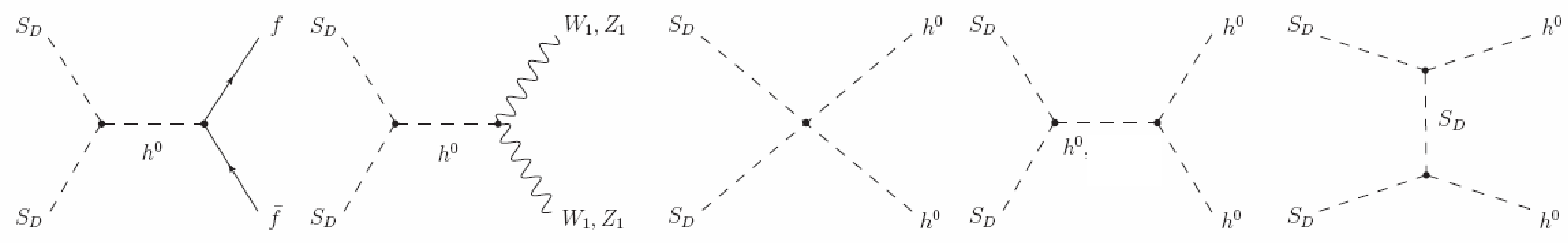
中国科学院理论物理研究所

暗物质与重子物质起源冬季研讨会 2010.12.13-15

The real singlet scalar dark matter model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S\,\partial^\mu S - \frac{m_0^2}{2}S^2 - \frac{\lambda_S}{4}S^4 - \lambda S^2 H^\dagger H$$

Z2



$$\hat{\sigma}_{ff} = \sum_f \frac{\lambda^2 m_f^2}{\pi}\frac{1}{(s-m_h^2)^2 + m_h^2\Gamma_h^2}\frac{(s-4m_f^2)^{1.5}}{\sqrt{s}},$$

$$\hat{\sigma}_{ZZ} = \frac{\lambda^2}{4\pi}\frac{s^2}{(s-m_h^2)^2 + m_h^2\Gamma_h^2}\sqrt{1-\frac{4m_Z^2}{s}}\left(1-\frac{4m_Z^2}{s}+\frac{12m_Z^4}{s^2}\right),$$

$$\hat{\sigma}_{WW} = \frac{\lambda^2}{2\pi}\frac{s^2}{(s-m_h^2)^2 + m_h^2\Gamma_h^2}\sqrt{1-\frac{4m_W^2}{s}}\left(1-\frac{4m_W^2}{s}+\frac{12m_W^4}{s^2}\right),$$

$$\hat{\sigma}_{hh} = \frac{\lambda^2}{4\pi}\sqrt{1-\frac{4m_h^2}{s}}\left[\left(\frac{s+2m_h^2}{s-m_h^2}\right)^2 - \frac{16\lambda v_{\rm EW}^2}{s-2m_h^2}\frac{s+2m_h^2}{s-m_h^2}F(\xi) + \frac{32\lambda^2 v_{\rm EW}^4}{(s-2m_h^2)^2}\left(\frac{1}{1-\xi_h^2}+F(\xi)\right)\right]$$

3 parameters

Dark matter relic density

Boltzmann Equation:

$$\frac{dY}{dx} = -\frac{x\,\mathbf{s}(x)}{H}\langle\sigma v\rangle(Y^2 - Y_{EQ}^2)\ , \qquad (11)$$

where $Y \equiv n/\mathbf{s}(x)$ denotes the dark matter number density. The entropy density $\mathbf{s}(x)$ and the Hubble parameter H evaluated at $x = 1$ are given by

$$\mathbf{s}(x) = \frac{2\pi^2 g_*}{45}\frac{m^3}{x^3}\ ; \qquad (12)$$

$$H = \sqrt{\frac{4\pi^3 g_*}{45}}\frac{m^2}{M_{PL}}\ , \qquad (13)$$

where $M_{PL} \simeq 1.22 \times 10^{19}$ GeV is the Planck energy. g_*

$$\langle\sigma v\rangle = \frac{1}{n_{EQ}^2}\frac{m_D}{64\pi^4 x}\int_{4m_D^2}^{\infty}\hat{\sigma}(s)\,\sqrt{s}K_1\!\left(\frac{x\sqrt{s}}{m_D}\right)ds\ ,$$

$$n_{EQ} = \frac{g_i}{2\pi^2}\frac{m_D^3}{x}K_2(x)\ ,$$

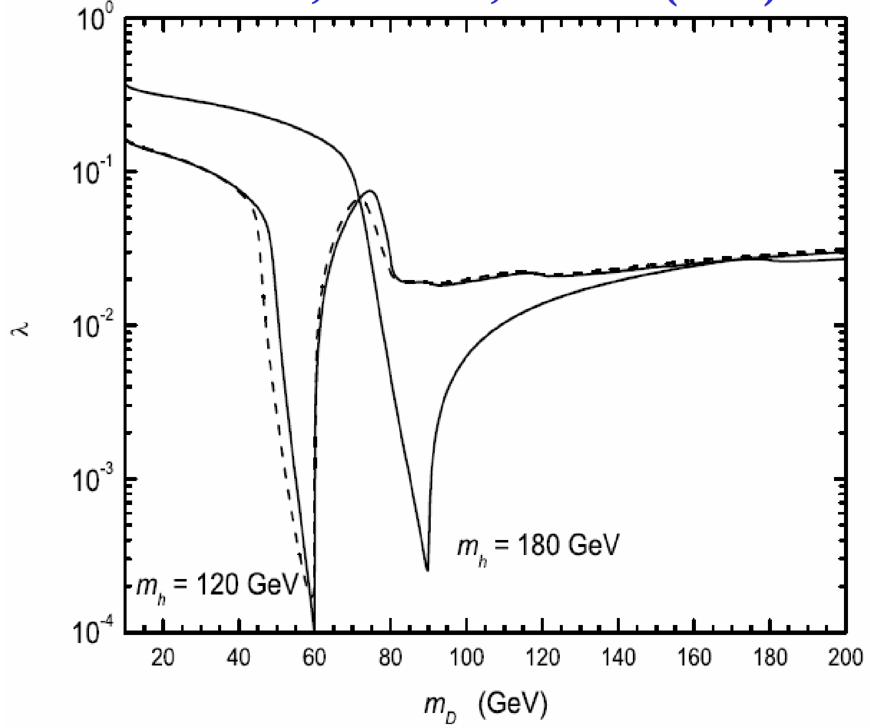
$$\hat{\sigma}(s) = \hat{\sigma}\, g_i^2\sqrt{1 - \frac{4m_D^2}{s}}\ ,$$

$$\boxed{\Omega_D h^2 = 2.74 \times 10^8\frac{m}{\mathrm{GeV}}Y_0}$$

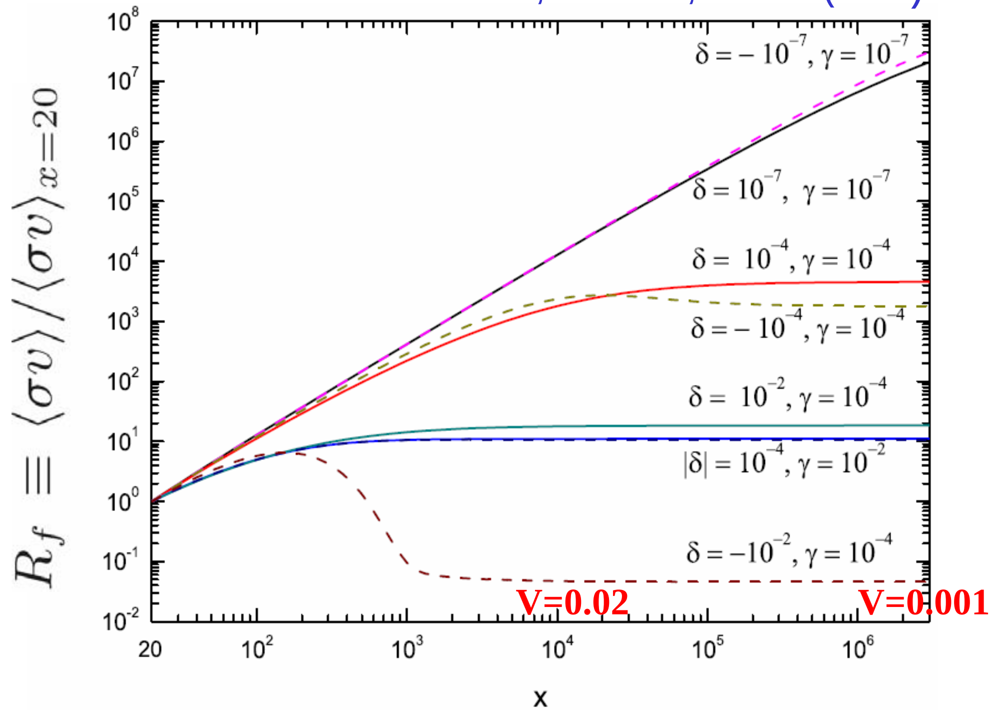
$$0.1088 \le \Omega_D h^2 \le 0.1158$$

Constraints from the DM relic density

W.L. Guo, Y.L. Wu, JHEP10(2010)083



W.L. Guo and Y.L. Wu, PRD 79,055012 (2009)



S-channel Resonance：

$$\sigma v \propto \frac{1}{(s-M^2)^2 + M^2\Gamma^2};$$

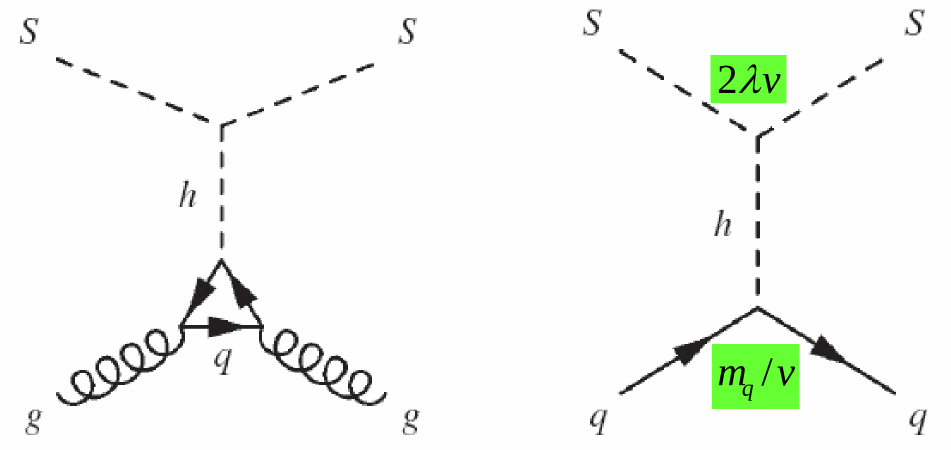
Resonance!

Breit-Wigner effect!
For PAMELA…

$$s \approx 4m^2(1+v^2)$$

The dark matter direct detection

For scalar interaction:



WIMP-nucleus cross section

$$\sigma_{\mathcal{N}} = \frac{4M^2(\mathcal{N})}{\pi}(Zf_p + (A-Z)f_n)^2 \,,$$

$$f_{p,n} = \sum_{q=u,d,s} f_{Tq}^{(p,n)} a_q \frac{m_{p,n}}{m_q} + \frac{2}{27} f_{TG}^{(p,n)} \sum_{q=c,b,t} a_q \frac{m_{p,n}}{m_q}$$

$$M(N) = m_D M_N / (m_D + M_N)$$
$$M(n) = m_D M_n / (m_D + M_n)$$

$$f_{Tu}^{(p)} = 0.020 \pm 0.004,\; f_{Td}^{(p)} = 0.026 \pm 0.005,\; f_{Ts}^{(p)} = 0.118 \pm 0.062,$$
$$f_{Tu}^{(n)} = 0.014 \pm 0.003,\; f_{Td}^{(n)} = 0.036 \pm 0.008,\; f_{Ts}^{(n)} = 0.118 \pm 0.062$$

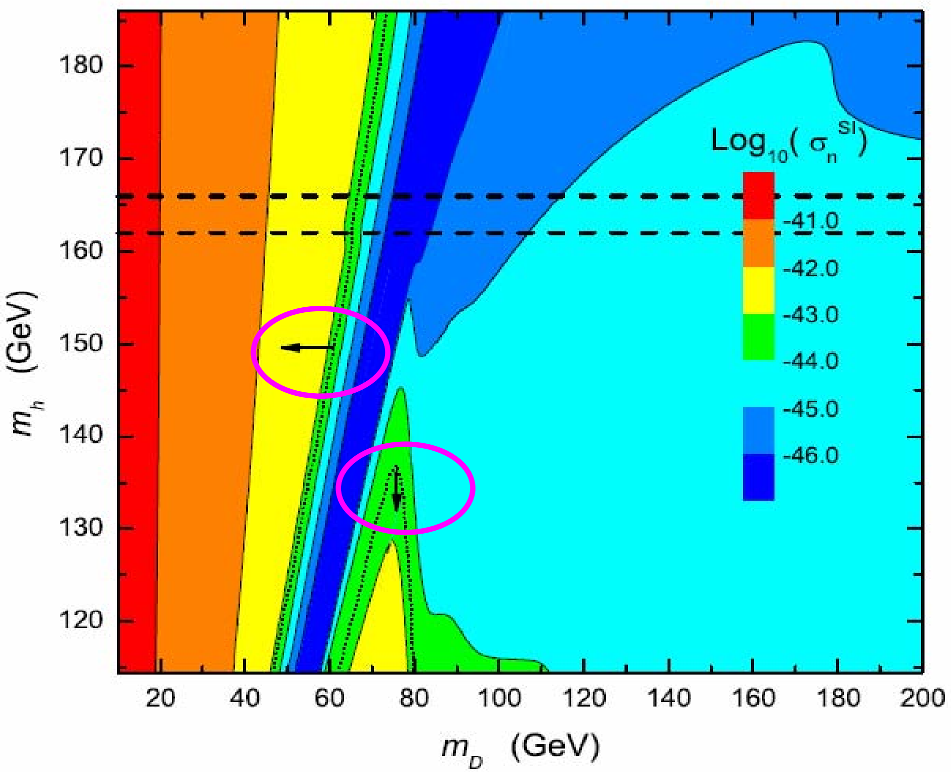
$$f_{TG}^{(p,n)} = 1 - \sum_{q=u,d,s} f_{Tq}^{(p,n)}$$

WIMP-nucleon cross section

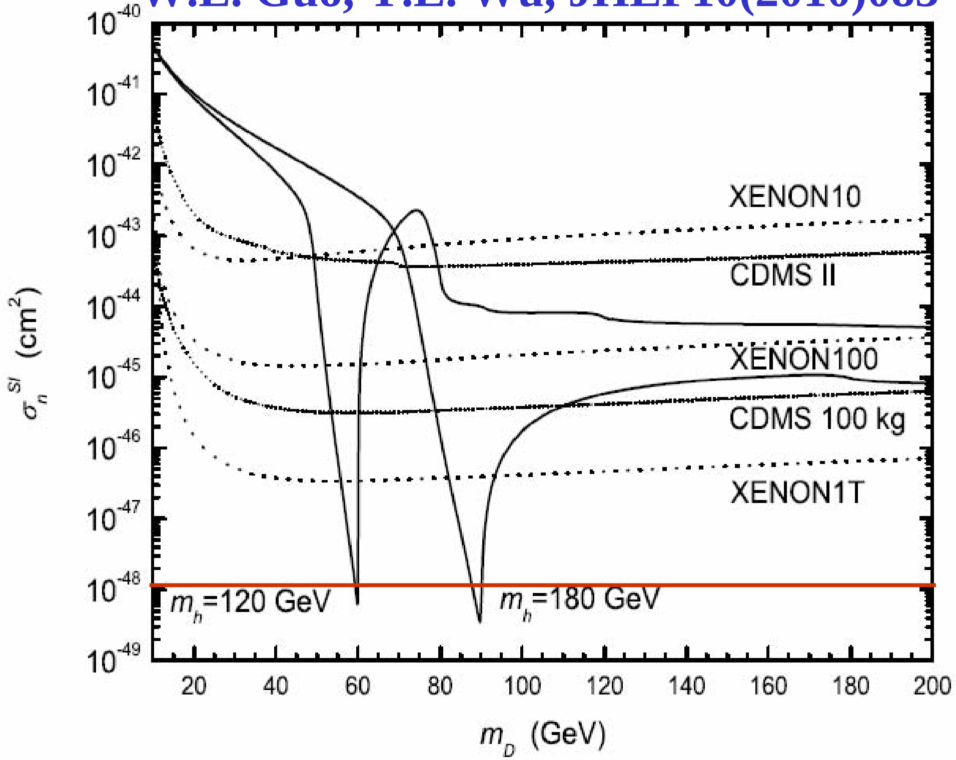
$$\sigma_n^{SI} = \left(\frac{m_D\, m_n}{m_D + m_n}\right)^2 \frac{1}{A^2 M^2(\mathcal{N})} \sigma_{\mathcal{N}} \approx \frac{4}{\pi}\left(\frac{m_D\, m_n}{m_D + m_n}\right)^2 f_n^2$$

$$a_q = \frac{\lambda m_q}{m_D m_h^2}$$

Constraints from the DM direct search



W.L. Guo, Y.L. Wu, JHEP10(2010)083



Two excluded regions!

Future experiments

Atmosphere neutrino!

A. Gutlein, et. al, 1003.5530

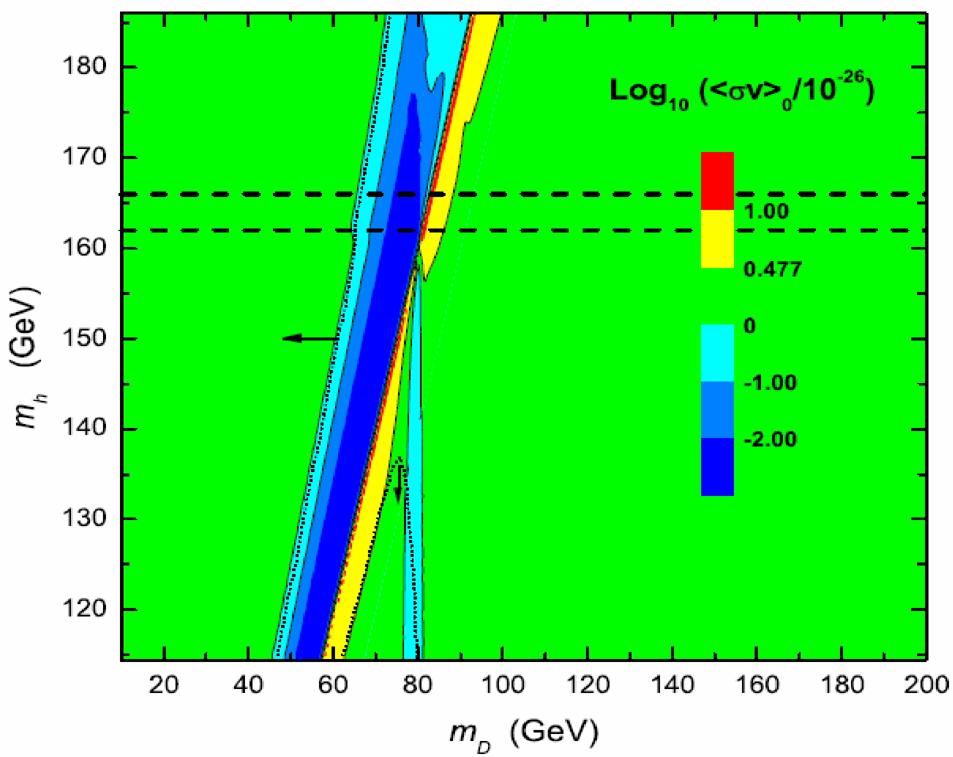
Constraints from the DM indirect search

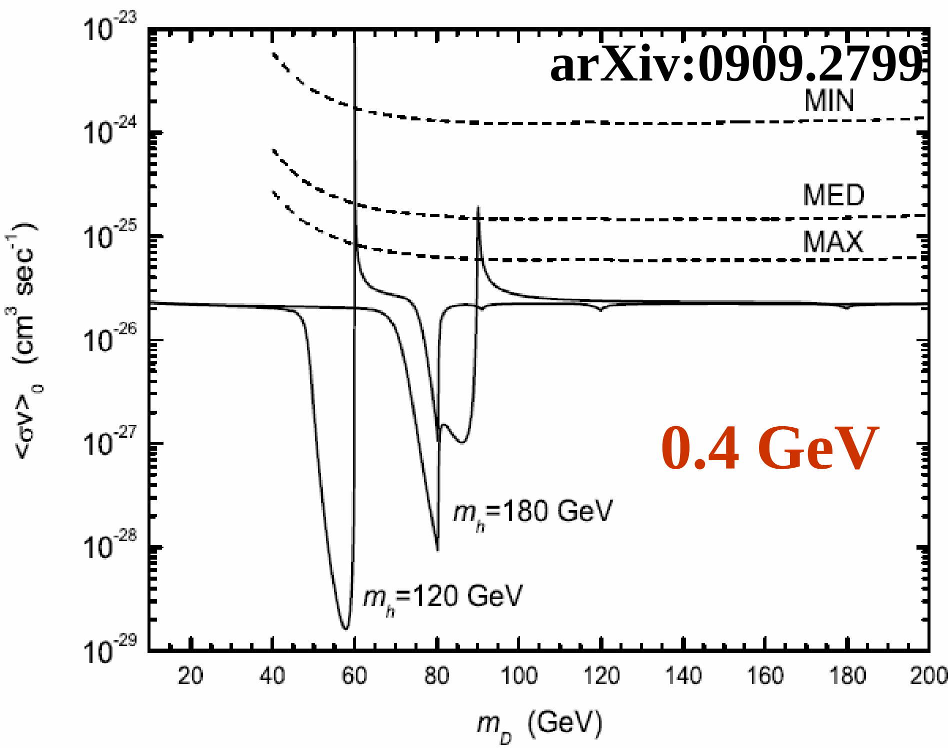
Thermally averaged annihilation cross section:

$$\langle \sigma v \rangle \equiv \frac{g_1 g_2 \int \frac{d^3 p_1}{(2\pi)^3} \frac{d^3 p_2}{(2\pi)^3} e^{-\frac{E_1}{T}} e^{-\frac{E_2}{T}} \frac{1}{4E_1E_2} \frac{d^3 p_3}{(2\pi)^3 2E_3} \frac{d^3 p_4}{(2\pi)^3 2E_4} |M|^2 (2\pi)^4 \delta^4(p_1+p_2+p_3+p_4)}{g_1 g_2 \int \frac{d^3 p_1}{(2\pi)^3} \frac{d^3 p_2}{(2\pi)^3} e^{-\frac{E_1}{T}} e^{-\frac{E_2}{T}}}$$

$x \equiv m_D / T = 3\times10^6$

σv



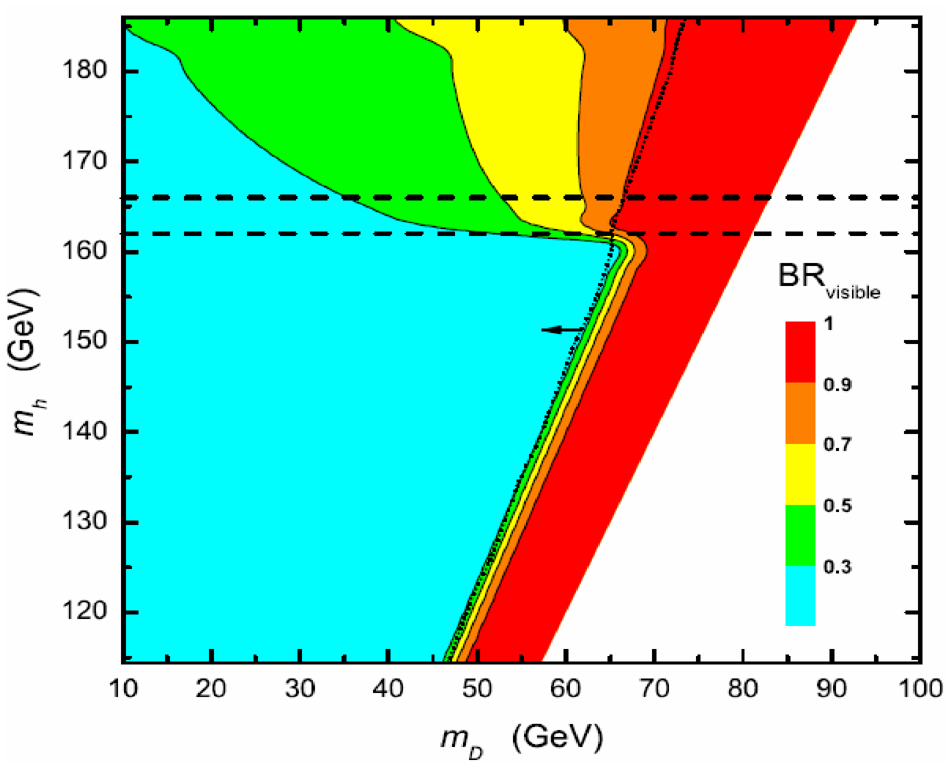


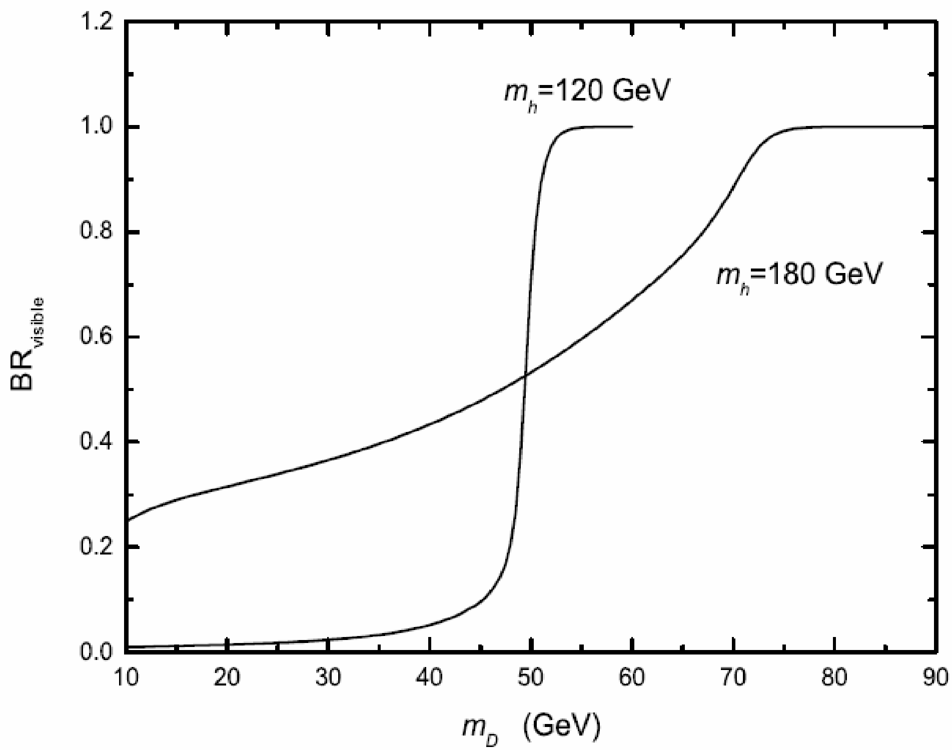
Both direct and indirect are very small for resonance region!

Implications on the Higgs search

The Higgs visible decay branching ratio:

$$\mathrm{BR_{visible}} = \frac{\Gamma_{h\to \mathrm{SM}}}{\Gamma_{h\to 2S} + \Gamma_{h\to \mathrm{SM}}}$$





Gauge singlet DM in the Left-Right model

W.L. Guo, L.M. Wang, Y.L. Wu, Y.F. Zhou and C. Zhuang, PRD 79, 055015 (2009)

Left-right symmetry model:

$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

right-handed gauge bosons,
right-handed neutrinos and

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \quad \Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}$$

P and CP properties:

If we introduce a gauge singlet $S = \frac{S_\sigma + iS_D}{\sqrt{2}}$ with $S \xrightarrow[\text{CP}]{\text{P}} \begin{matrix} S \\ S^* \end{matrix}$ and $S^* \xrightarrow[\text{CP}]{\text{P}} \begin{matrix} S^* \\ S \end{matrix}$

	P	CP		P	CP		P	CP
ϕ	$\phi^\dagger$	ϕ^*	$S+S^*$	+	+	$S-S^*$	+	-
χ	$\chi^\dagger$	χ^*	SS^*	+	+	$\mathrm{Tr}(\phi^\dagger\phi)$	+	+
$\Delta_{L(R)}$	$\Delta_{R(L)}$	$\Delta^*_{L(R)}$	$\mathrm{Tr}(\phi^\dagger\tilde{\phi}+\tilde{\phi}^\dagger\phi)$	+	+	$\mathrm{Tr}(\phi^\dagger\tilde{\phi}-\tilde{\phi}^\dagger\phi)$	-	-
S	S	S^*	$\mathrm{Tr}(\Delta_L^\dagger\Delta_L+\Delta_R^\dagger\Delta_R)$	+	+	$\mathrm{Tr}(\Delta_L^\dagger\Delta_L-\Delta_R^\dagger\Delta_R)$	-	+

Unique way!

SSB and Mass spectrum in 1HBDM

After the SSB:

$$\langle \phi^0_{1,2} \rangle = \frac{\kappa_{1,2}}{\sqrt{2}} \quad \text{and} \quad \langle \delta^0_{L,R} \rangle = \frac{v_{L,R}}{\sqrt{2}}$$

$$\kappa = \sqrt{|\kappa_1|^2 + |\kappa_2|^2} = 246 \text{ GeV}$$

Mass spectrum :

$$\left\{ \begin{array}{l} v_L \approx 0 \\ \kappa_1 \gg \kappa_2 \\ v_R \sim 10 \text{ TeV} \end{array} \right\} \Rightarrow$$

Particles	Mass^2	Particles	Mass^2
$h^0 = \phi_1^{0r}$	$m^2_{h^0} = 2\lambda_1 \kappa^2$	$H_1^\pm = \phi_1^\pm$	$m^2_{H_1^\pm} = \frac{1}{2}\alpha_3 v_R^2$
$H_1^0 = \phi_2^{0r}$	$m^2_{H_1^0} = \frac{1}{2}\alpha_3 v_R^2$	$H_R^{\pm\pm} = \delta_R^{\pm\pm}$	$m^2_{H_R^{\pm\pm}} = 2\rho_2 v_R^2$
$A_1^0 = -\phi_2^{0i}$	$m^2_{A_1^0} = \frac{1}{2}\alpha_3 v_R^2$	$H_L^\pm = \delta_L^\pm$	$m^2_{H_L^\pm} = \frac{1}{2}(\rho_3 - 2\rho_1) v_R^2$
$H_2^0 = \delta_R^{0r}$	$m^2_{H_2^0} = 2\rho_1 v_R^2$	$H_L^{\pm\pm} = \delta_L^{\pm\pm}$	$m^2_{H_L^{\pm\pm}} = \frac{1}{2}(\rho_3 - 2\rho_1) v_R^2$
$H_3^0 = \delta_L^{0r}$	$m^2_{H_3^0} = \frac{1}{2}(\rho_3 - 2\rho_1) v_R^2$	$A_L^0 = \delta_L^{0i}$	$m^2_{A_L^0} = \frac{1}{2}(\rho_3 - 2\rho_1) v_R^2$
Z_1	$m^2_{Z_1} = m^2_{W_1} \sec^2\theta_W$	$W_1^\pm = W_L^\pm$	$m^2_{W_1} = g^2\kappa^2/4$
Z_2	$m^2_{Z_2} = \frac{g^2 v_R^2 \cos^2\theta_W}{\cos 2\theta_W}$	$W_2^\pm = W_R^\pm$	$m^2_{W_2} = g^2 v_R^2/2$

Dark matter mass and interactions

For WIMP: $10\ \text{GeV} \le m_D \le 1\ \text{TeV}$

$v_R \sim 10\ \text{TeV} \Rightarrow$ An approximate global symmetry:

$$S \xrightarrow{\text{U(1)}} e^{iq} S \quad \Rightarrow \quad \text{light DM mass}$$

$$\Rightarrow\ S \not+ S^*$$

Higgs potential related to the Singlet:

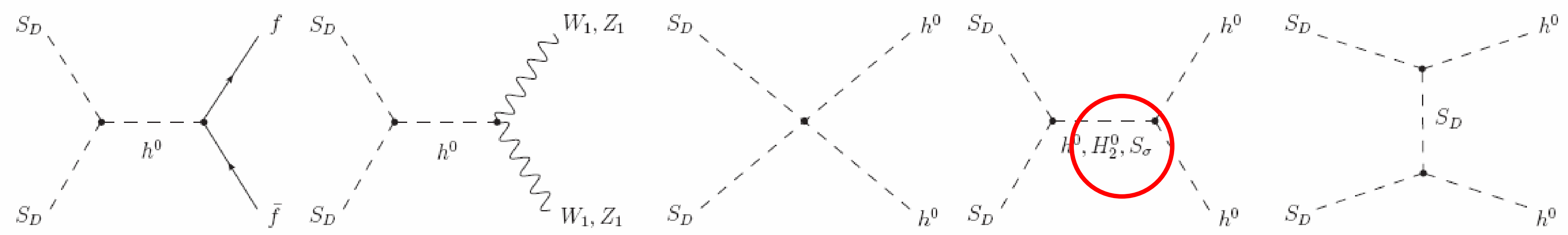
$$\mathcal{V}_S = -\mu_D^2 S S^* + \lambda_D (S S^*)^2 + \sum_{i=1}^{3} \lambda_{i,D} S S^* O_i - \frac{m_D^2}{4}(S - S^*)^2$$

$O_1 = \mathrm{Tr}(\phi^\dagger \phi)$, $O_2 = \mathrm{Tr}(\phi^\dagger \tilde{\phi} + \tilde{\phi}^\dagger \phi)$ and $O_3 = \mathrm{Tr}(\Delta_L^\dagger \Delta_L + \Delta_R^\dagger \Delta_R)$.

Interaction	Vertex	Interaction	Vertex	Interaction	Vertex	Interaction	Vertex
$S_D S_D S_\sigma S_\sigma$	$-i2\lambda_D$	$S_D S_D h^0$	$-i\lambda_{1,D}\kappa$	$S_D S_D S_\sigma$	$-i2\lambda_D v_\sigma$	$S_D S_D H_2^0$	$-i\lambda_{3,D} v_R$
$S_D S_D H H^*$	$-i\lambda_{1,D}$	$S_\sigma S_\sigma h^0$	$-i\lambda_{1,D}\kappa$	$H H^* S_\sigma$	$-i\lambda_{1,D} v_\sigma$	$S_\sigma S_\sigma H_2^0$	$-i\lambda_{3,D} v_R$
$S_D S_D h^0 H_1^0$	$-i2\lambda_{2,D}$	$S_D S_D H_1^0$	$-i2\lambda_{2,D}\kappa$	$h^0 H_1^0 S_\sigma$	$-i2\lambda_{2,D} v_\sigma$	$S_\sigma S_\sigma S_\sigma$	$-i6\lambda_D v_\sigma$
$S_D S_D \Delta\Delta^*$	$-i\lambda_{3,D}$	$S_\sigma S_\sigma H_1^0$	$-i2\lambda_{2,D}\kappa$	$\Delta\Delta^* S_\sigma$	$-i\lambda_{3,D} v_\sigma$	$h^0 h^0 H_2^0$	$-i\alpha_1 v_R$

$H H^* = \{H_0 H_0, H_1 H_1, A_1 A_1, H^+ H^-\}$; $\Delta\Delta^* = \{\delta_L^0 \delta_L^{0*}, \delta_L^+ \delta_L^-, \delta_L^{++} \delta_L^{--}, \delta_R^{++} \delta_R^{--}, H_2 H_2\}$

Dark matter annihilation in 1HBDM



Same as the simplest DM model before Higgs channel is open!

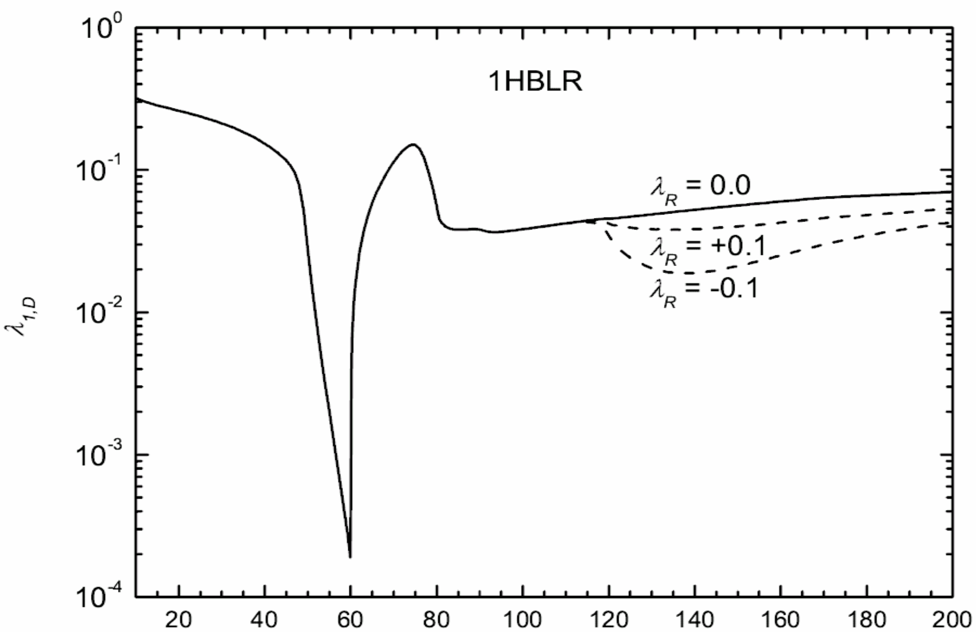
$$\hat{\sigma}_{h^0h^0} = \frac{\lambda_{1,D}^2}{16\pi}\sqrt{1-\frac{4m_{h^0}^2}{s}}\left[G_1^2 - \frac{8\lambda_{1,D}\kappa^2}{s-2m_{h^0}^2}G_1F(\xi_{h^0}) + \frac{8\lambda_{1,D}^2\kappa^4}{(s-2m_{h^0}^2)^2}\left(\frac{1}{1-\xi_{h^0}^2}+F(\xi_{h^0})\right)\right]$$

$$G_1 = 1 + \frac{3m_{h^0}^2}{s-m_{h^0}^2} + \frac{\alpha_1\lambda_{3,D}v_R^2}{s-m_{H_2^0}^2}\frac{1}{\lambda_{1,D}} + \frac{m_\sigma^2}{s-m_\sigma^2}$$

$$m_{H_2^0}^2 = 2\rho_1 v_R^2 \rightarrow \lambda_R \equiv \alpha_1\lambda_{3,D}/(2\rho_1)$$

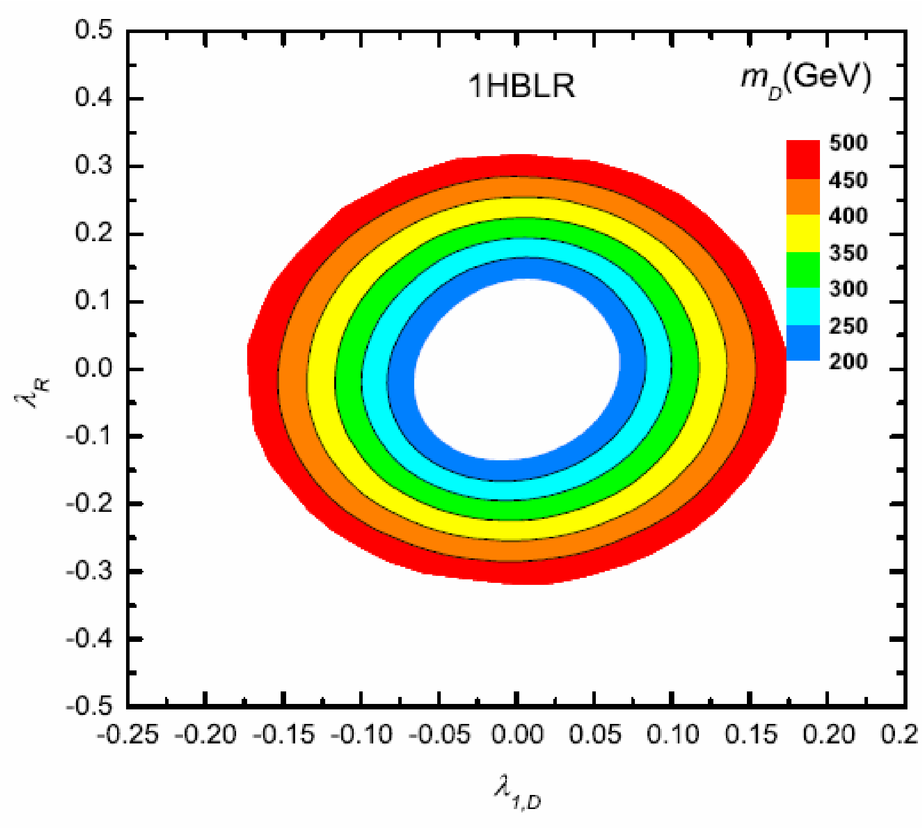
$$F(\xi_{h^0}) \equiv \operatorname{arctanh}(\xi_{h^0})/\xi_{h^0}$$

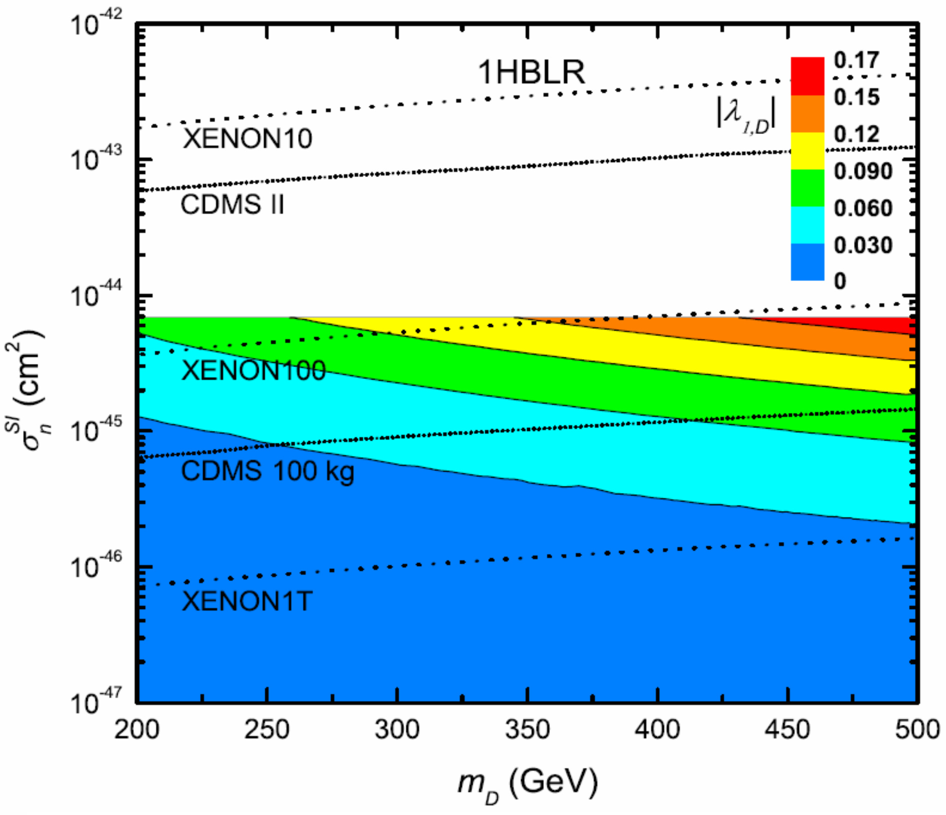
$$\xi_{h^0} = \sqrt{s-4m_D^2}\sqrt{s-4m_{h^0}^2}/(s-2m_{h^0}^2)$$



Parameter space for 200 GeV -500 GeV

W.L. Guo, Y.L. Wu, Y.F. Zhou,arXiv:1008.4479





Central **Continuous**

LR symmetric two Higgs bidoublet model (2HBDM)

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix},\ \chi = \begin{pmatrix} \chi_1^0 & \chi_1^+ \\ \chi_2^- & \chi_2^0 \end{pmatrix} \xrightarrow[\kappa_2 \sim w_2 \sim 0]{\text{SSB}} \phi' = \begin{pmatrix} \frac{h_1+v}{\sqrt{2}} & \phi'^+_1 \\ 0 & \phi'^0_2 \end{pmatrix},\ \chi' = \begin{pmatrix} \frac{h_2+ih_3}{\sqrt{2}} & \chi'^+_1 \\ h^- & \chi'^0_2 \end{pmatrix}$$

Light Higgs mixing:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} c_x c_z & s_x c_z & s_z \\ -c_x s_y s_z - s_x c_y & -s_x s_y s_z + c_x c_y & s_y c_z \\ -c_x c_y s_z + s_x s_y & -s_x c_y s_z - c_x s_y & c_y c_z \end{pmatrix} \begin{pmatrix} h \\ H \\ A \end{pmatrix}$$

$\Rightarrow$

Case I: θ_x=60^o, θ_y=60^o, θ_z=150^o

Case II: θ_x=30^o, θ_y=0^o, θ_z=0^o

Case III: θ_x=0^o, θ_y=90^o, θ_z=75^o

Yukawa interactions:

$$-\mathcal{L}_Y = \overline{Q_L}\left(Y^\phi \phi' + \tilde{Y}^\phi \tilde{\phi}' + Y^\chi \chi' + \tilde{Y}^\chi \tilde{\chi}'\right) Q_R + h.c.,$$

Complex symmetric!

$$-\mathcal{L}_{LH} = \frac{h_1 + v_{\rm EW}}{\sqrt{2}}\left(\overline{u'_L} Y^{\phi'} u'_R + \overline{d'_L} \tilde{Y}^{\phi'} d'_R\right) + \frac{h_2 + ih_3}{\sqrt{2}} \overline{u'_L} Y^{\chi'} u'_R + \frac{h_2 - ih_3}{\sqrt{2}} \overline{d'_L} \tilde{Y}^{\chi'} d'_R + h.c.$$

$\Rightarrow$ $Y_{qq}^{\phi'} = \sqrt{2} m_q / v_{\rm EW}$ and $\tilde{Y}_{qq}^{\phi'} = \sqrt{2} m_q / v_{\rm EW}$

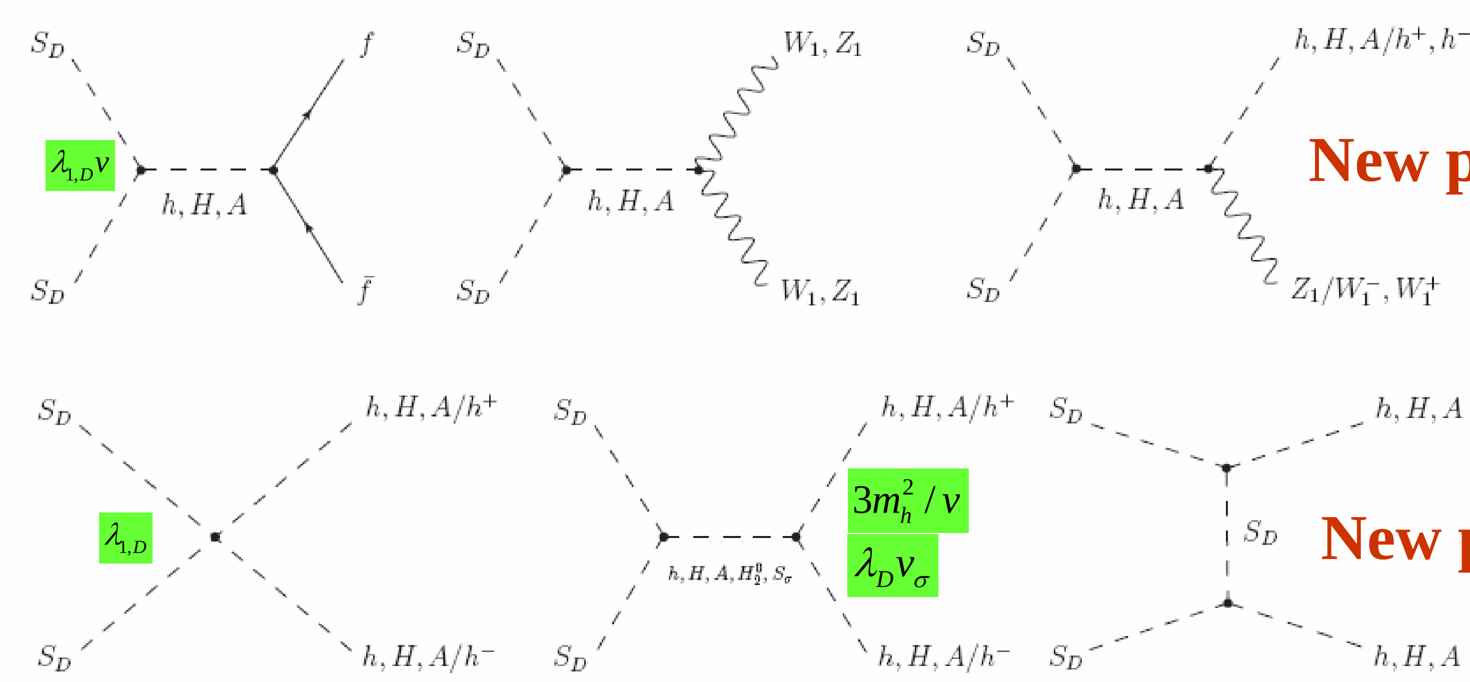
$Y_{qq}^{\chi'} = R\, Y_{qq}^{\phi'}$ and $\tilde{Y}_{qq}^{\chi'} = R\, \tilde{Y}_{qq}^{\phi'}$

Diagonal!

$R = 1$

$R = 5$

Dark matter annihilation in 2HBLR



New processes

New products

$m_H,\ m_A,\ m_{h^\pm}\ =\ 180\ \text{GeV and}\ m_h\ =\ 120\ \text{GeV}$

WIMP-quark coupling:

$$a_q = \frac{\lambda_{1,D}\, m_q}{2m_D}\left(\frac{f_1}{m_h^2} + \frac{f_3}{m_H^2} + \frac{f_5}{m_A^2}\right)$$

$f_{2,4,6}$ Velocity dependent!

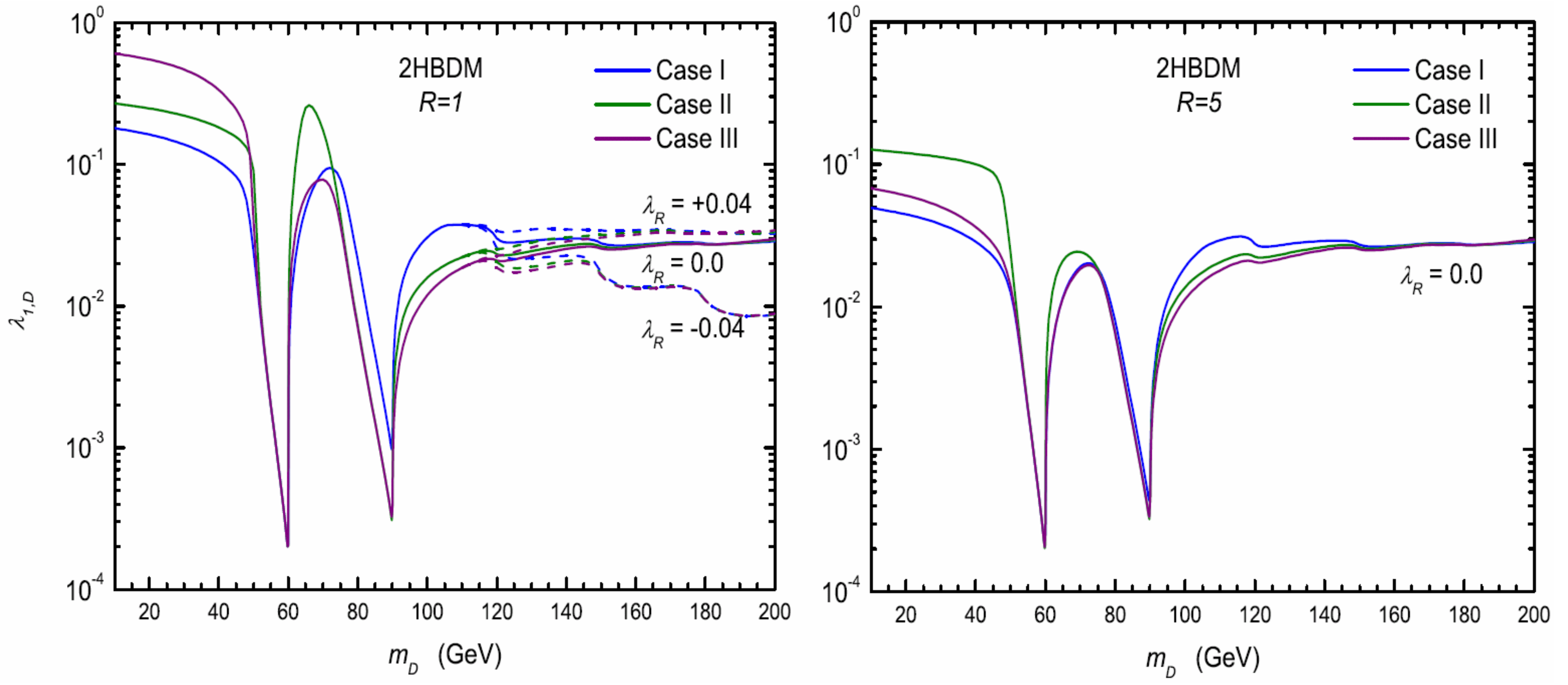
$$f_1 = c_x c_z - R c_y s_x - R c_x s_y s_z\ ,\quad f_2 = R s_x s_y - R c_x c_y s_z\ ,$$

$$f_3 = R c_x c_y + c_z s_x - R s_x s_y s_z\ ,\quad f_4 = -R s_x s_z c_y - R c_x s_y\ ,$$

$$f_5 = R s_y c_z + s_z\ ,\qquad f_6 = R c_y c_z\ .$$

Numerical results for coupling

W.L. Guo, Y.L. Wu, Y.F. Zhou,arXiv:1008.4479

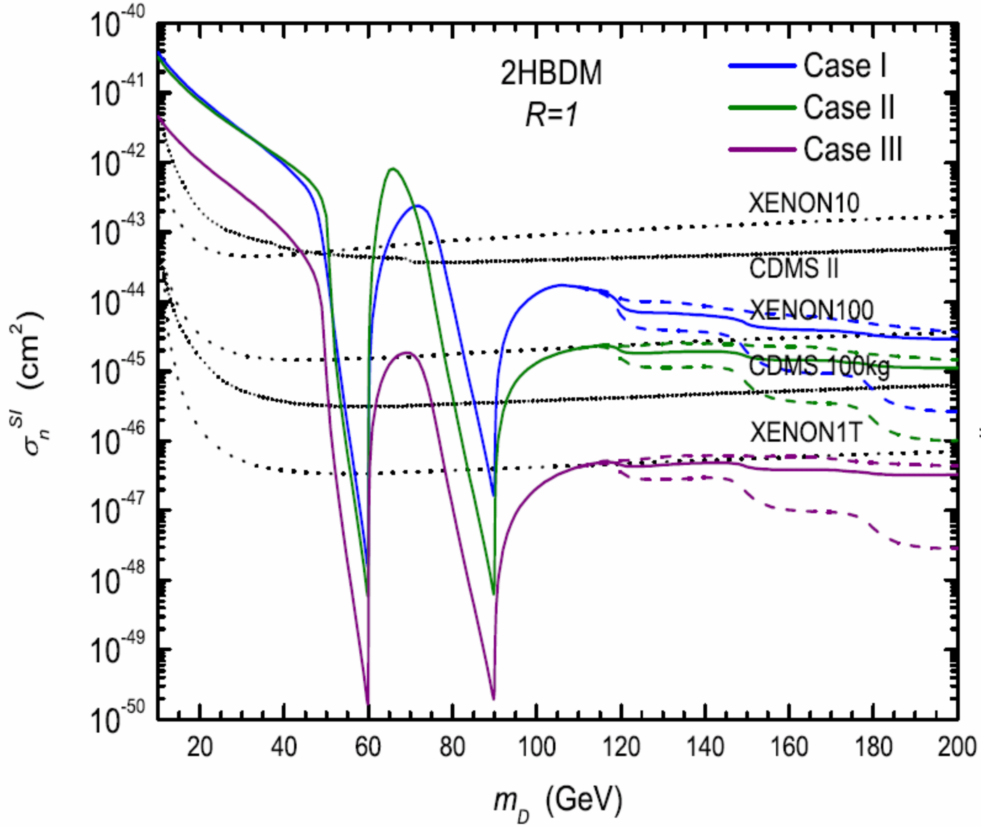


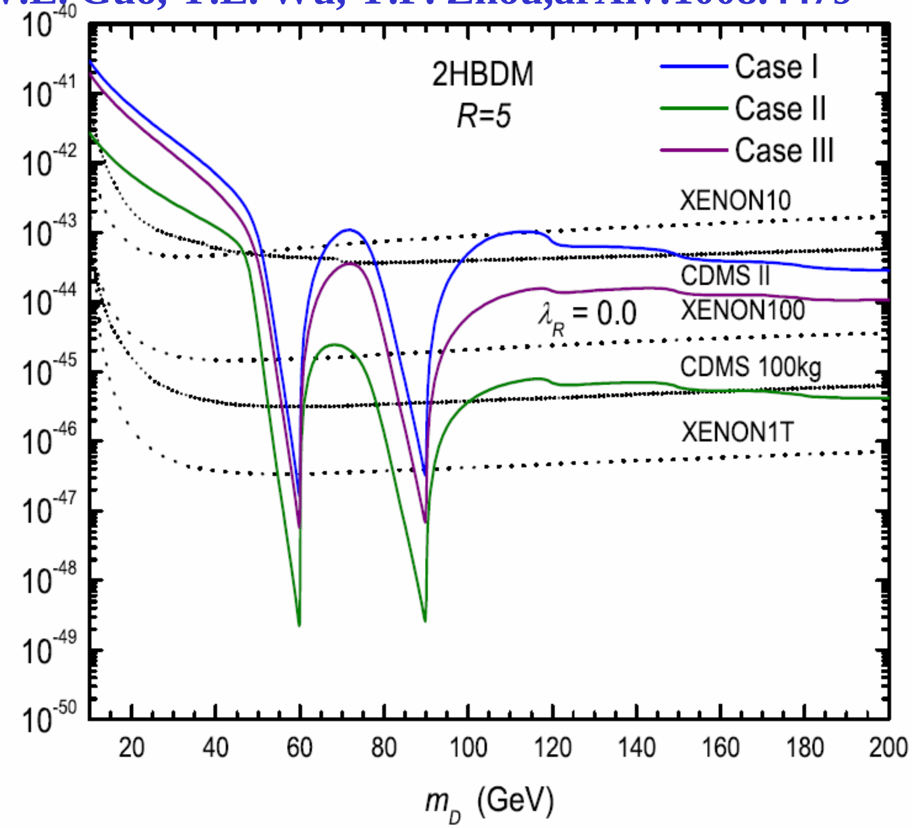
dependent on mixing and R for $m_D < 120$ GeV

Independent of R and mixing for $m_D > 120$ GeV

Numerical results for direct search

W.L, Guo, Y.L. Wu, Y.F. Zhou,arXiv:1008.4479





Depend on R and mixing

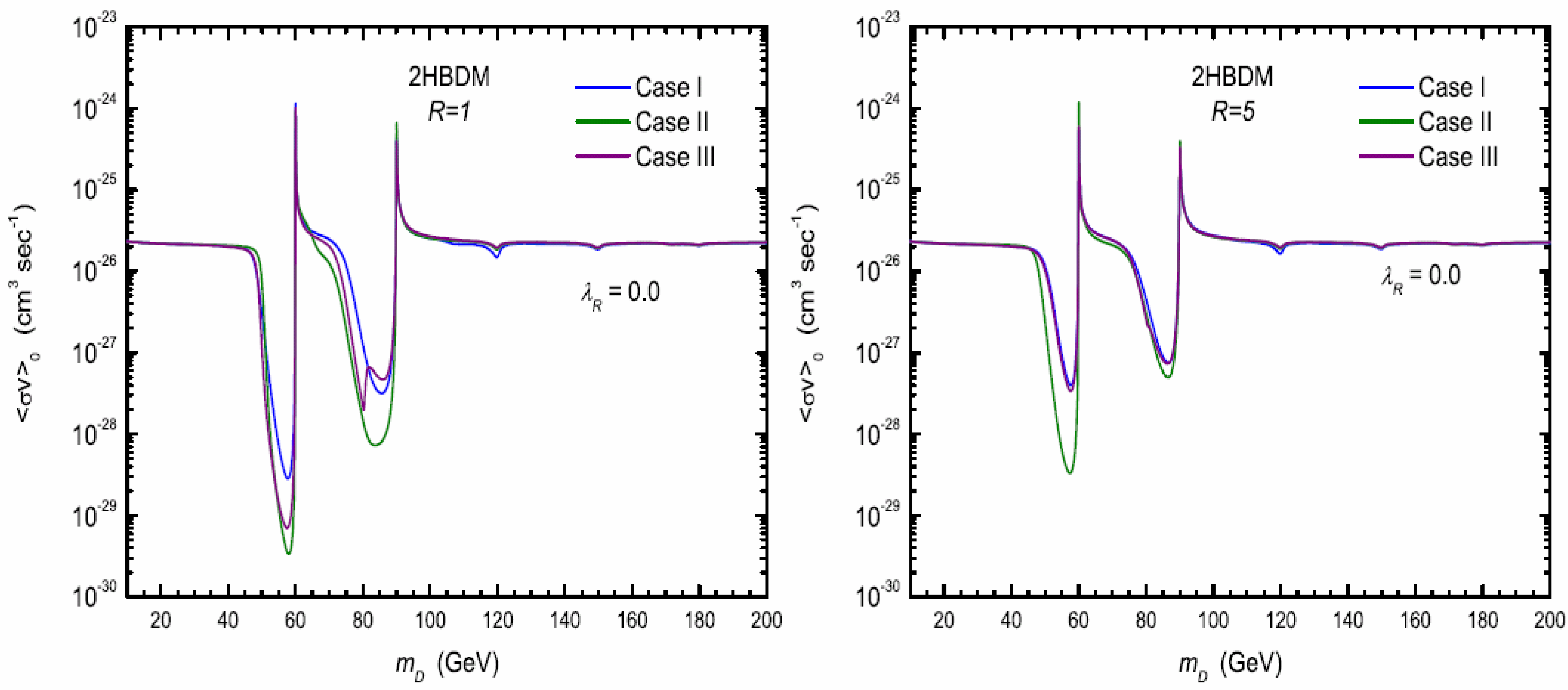
Case I III: enhanced

Case II: suppressed

Two resonances:
More

Numerical results for indirect search

W.L. Guo, Y.L. Wu, Y.F. Zhou,arXiv:1008.4479

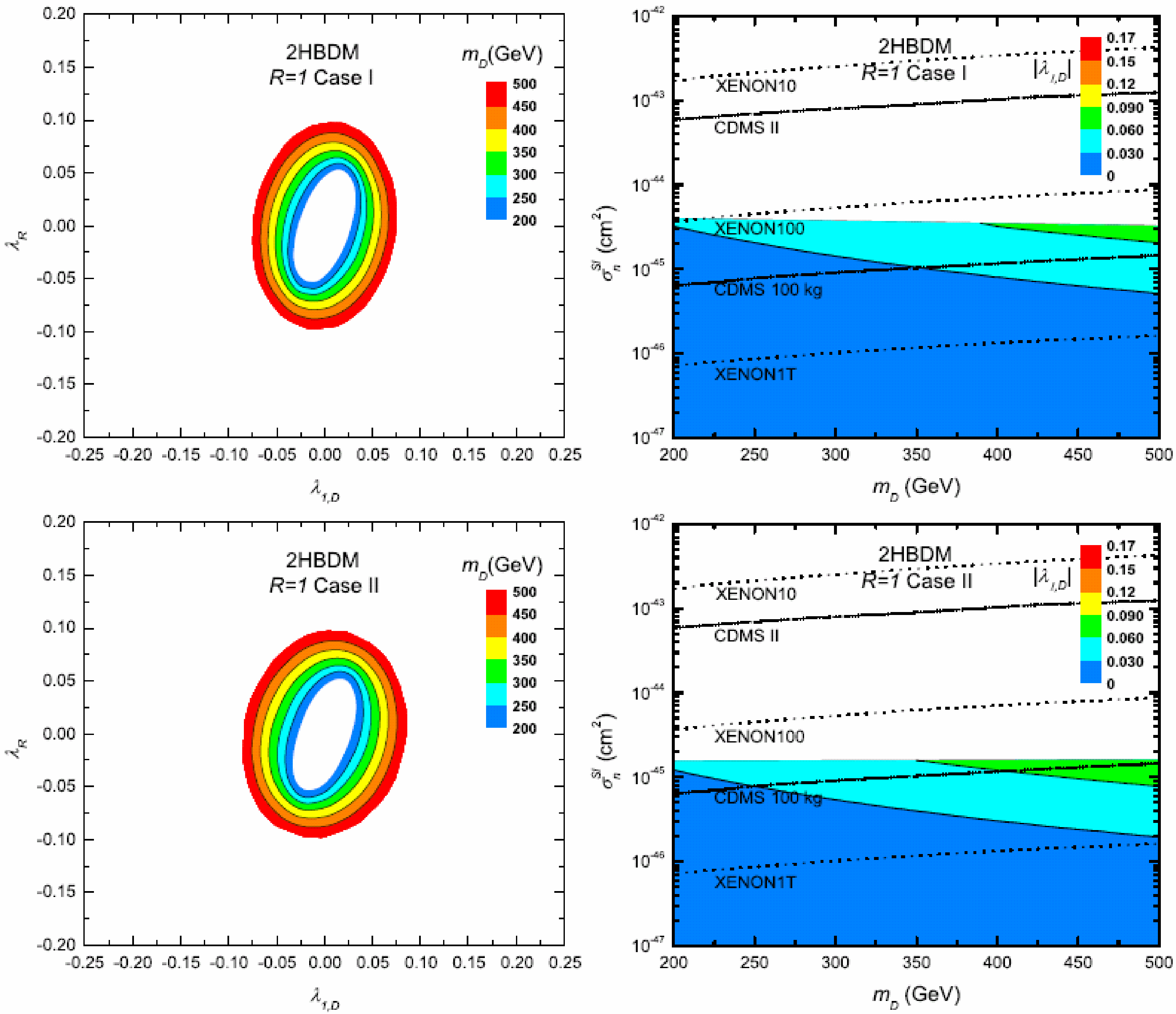


$$\langle \sigma v \rangle_0 \approx 2.3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{sec}^{-1}$$

Independent of R and mixing

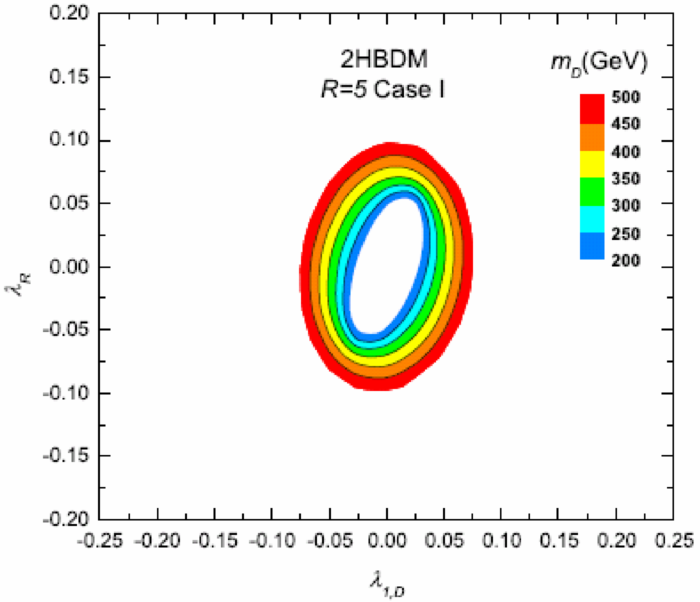
Direct and Indirect are very small!

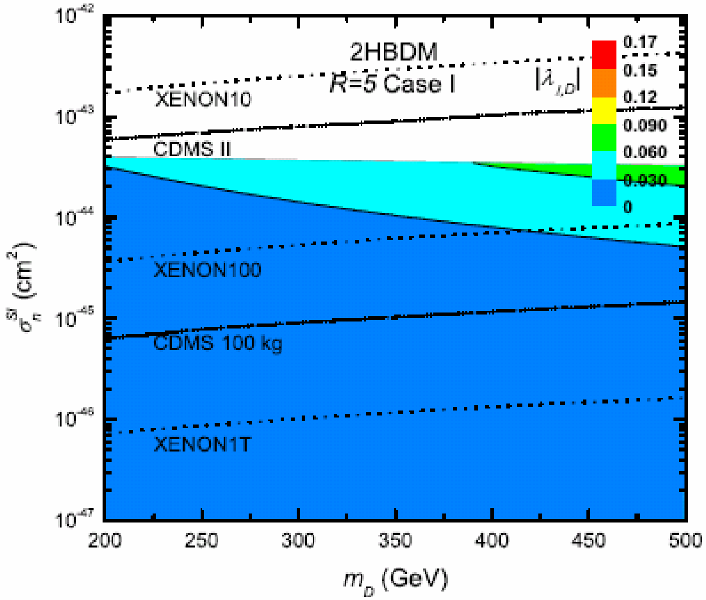
Numerical results for $200 < m_D < 500$ with R=1



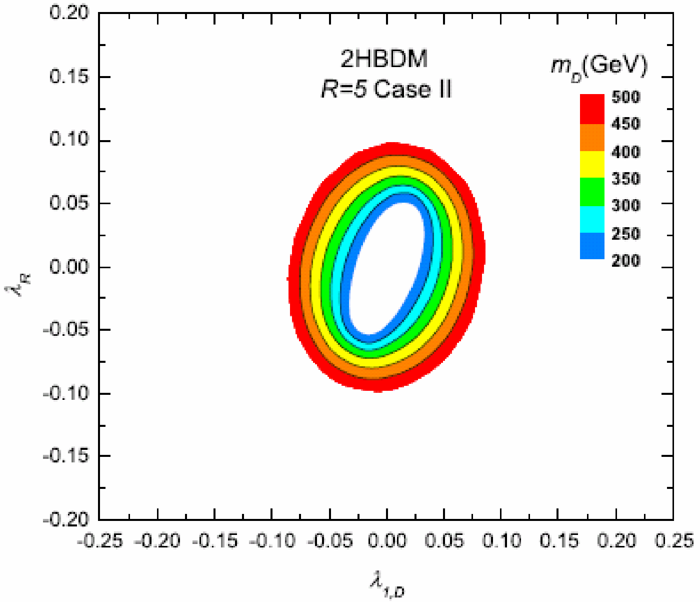
Same with 10-200 GeV

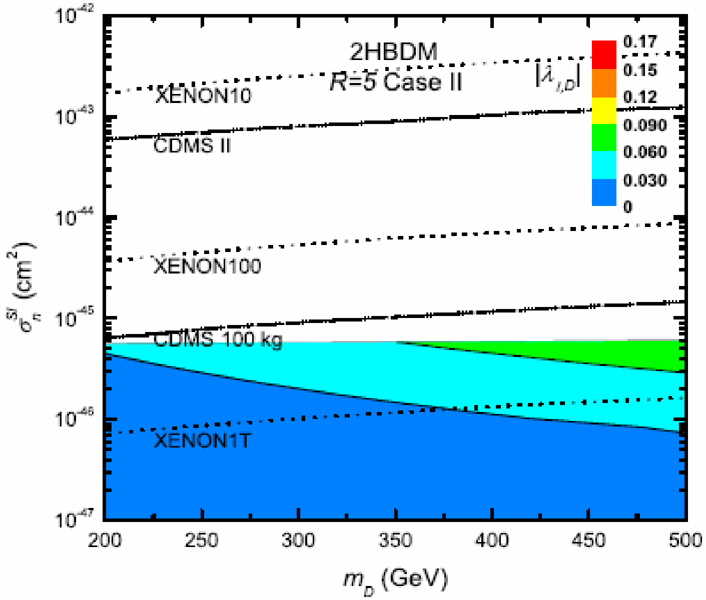
Numerical results for $200 < m_D < 500$ with R=5





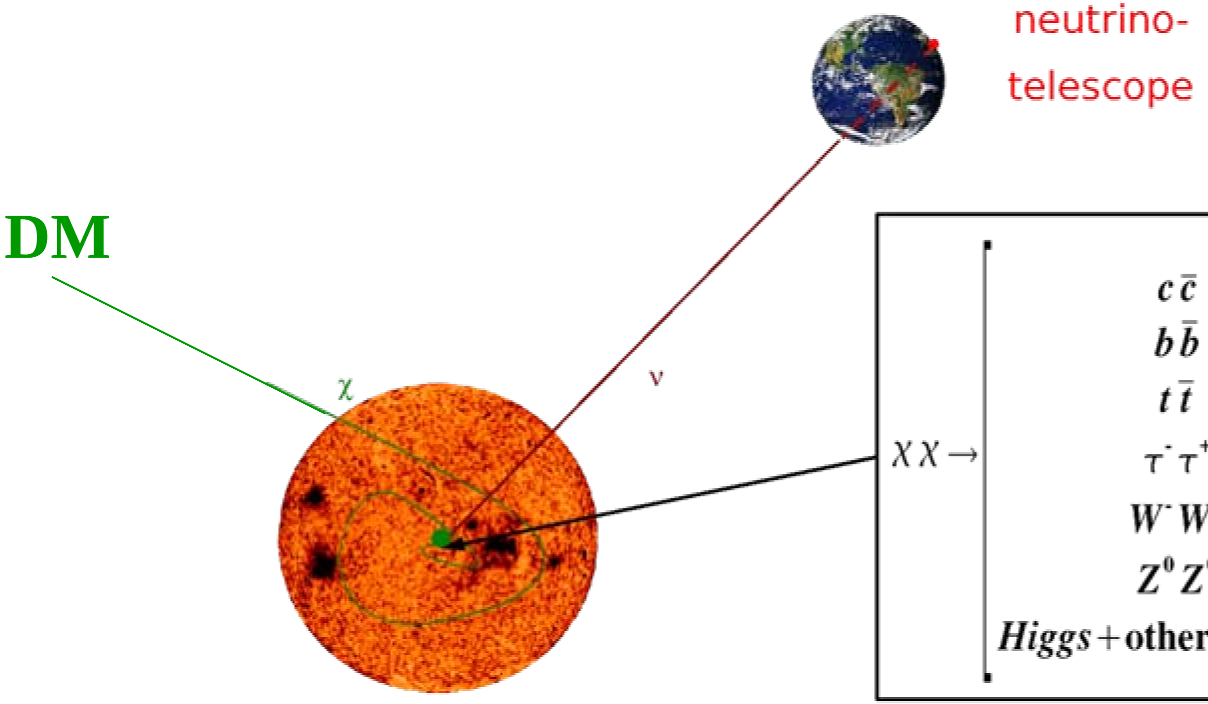
Case I: enhanced





Case II: suppressed cancellation

DM captured and annihilation in the Sun



$$\chi\chi \rightarrow \begin{bmatrix} c\bar{c} \\ b\bar{b} \\ t\bar{t} \\ \tau^-\tau^+ \\ W^-W^+ \\ Z^0Z^0 \\ Higgs + \text{other particles} \end{bmatrix} \rightarrow \nu + \bar{\nu} + \text{other particles}$$

DM elastic scattering in the Sun ➡ **DM captured when $V_{DM} < V_{esc}$** ➡ **Instantaneous thermalization**

DM capture and annihilation rates

The evolution of DM number in the Sun:

$$\dot{N} = C_\odot - C_A N^2$$

$$C_\odot \approx 1.25 \times 10^{21} s^{-1} \left(\frac{\rho_{DM}}{0.3\text{GeV/cm}^3}\right)\left(\frac{270\text{km/s}}{\bar{v}}\right)\left(\frac{1\text{GeV}}{m_D}\right)\left[\frac{\sigma_H^{SI}}{10^{-44}\text{cm}^2} S\left(\frac{m_D}{m_H}\right) + 0.073\frac{\sigma_{He}^{SI}}{10^{-44}\text{cm}^2} S\left(\frac{m_D}{m_{He}}\right)\right]$$

$$S(x) = \left[\frac{A(x)^{1.5}}{1 + A(x)^{1.5}}\right]^{2/3}, \quad A(x) = \frac{3x}{2(x-1)^2}\left(\frac{\langle v_{esc}\rangle}{\bar{v}}\right)^2$$

$$C_A = \frac{\langle \sigma v\rangle}{V_{\text{eff}}}, \quad V_{\text{eff}} = 6.74 * 10^{30}\text{cm}^3 \left(\frac{1\text{GeV}}{m_D}\right)^{3/2}$$

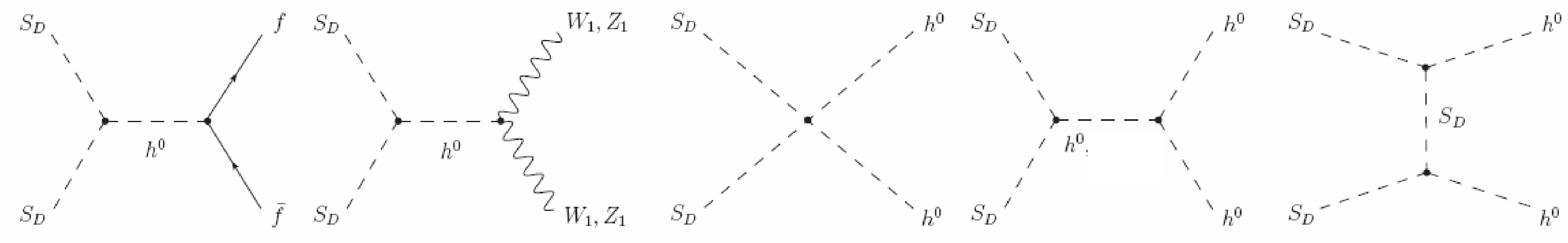
DM distribution in the Sun

The DM annihilation rate in the Sun:

$$\Gamma_{\text{ANN}} = \frac{1}{2} C_A N^2 = \frac{1}{2} C_\odot \tanh^2 (t_\odot \sqrt{C_\odot C_A})$$

$>> 1$

The flux of neutrinos at the Earth



$$\frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}} = \frac{\Gamma_{\rm ANN}}{4\pi R^2}\boxed{\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}}}$$

- Differential spectrum
- Neutrino interactions
- Neutrino oscillations

T. Schwetz, et. al, 0808.2016V3

parameter	best fit
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.23}_{-0.18}$
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$
$\sin^2\theta_{13}$ **= 0**	$0.013^{+0.013}_{-0.009}$

WIMPSIM !

M. Blennow, et. al., 0709.3898

Neutrino induced upward muon flux in Super-K

Neutrino induced upward muon flux:

$$\Phi_\mu = \int_{E_{thr}}^{m_D} dE_\mu \int_{E_\mu}^{m_D} dE_{\nu_\mu} \frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}} \int_0^\infty dX \int_{E_\mu}^{E_{\nu_\mu}} dE'_\mu g(X, E_\mu, E'_\mu) \left[\frac{d\sigma^p_{\nu_\mu}(E_{\nu_\mu}, E'_\mu)}{dE'_\mu} r_p + \frac{d\sigma^n_{\nu_\mu}(E_{\nu_\mu}, E'_\mu)}{dE'_\mu} r_n \right] + (\nu_\mu \to \bar{\nu}_\mu)$$

E_{thr} = 1.6 GeV

Approximation: T.K. Gaisser and T. Stanev, PRD 30,985 (1984)

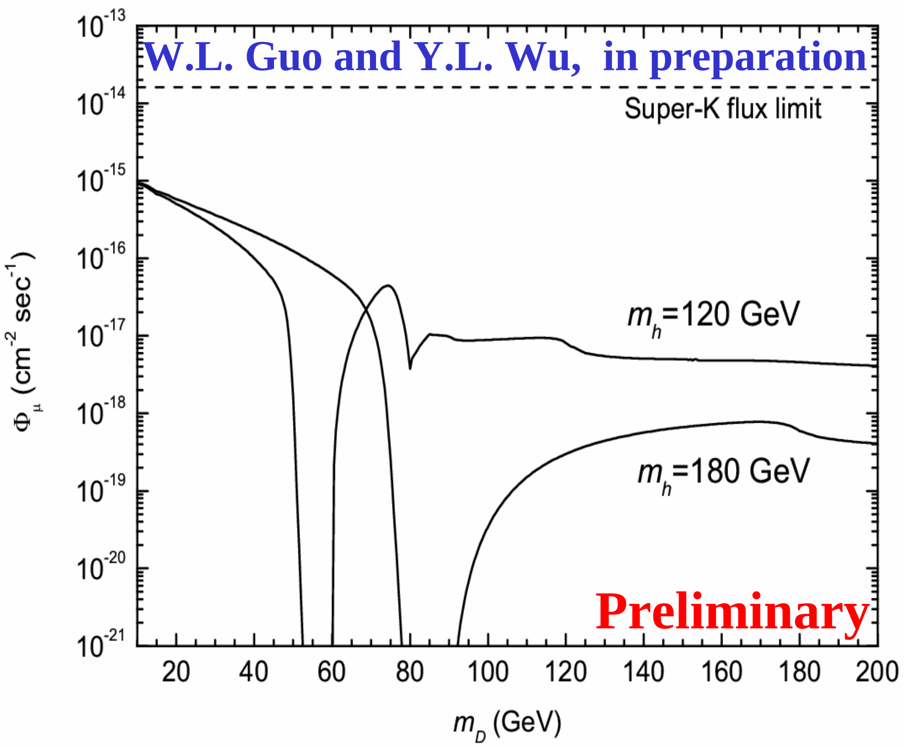
g is the probability that a muon of initial energy E`_\mu has energy E_\mu after propagating a distance X in rock.

$$g(X, E_\mu, E'_\mu) = \frac{\delta(X - X_0)}{\alpha + \beta E_\mu},$$

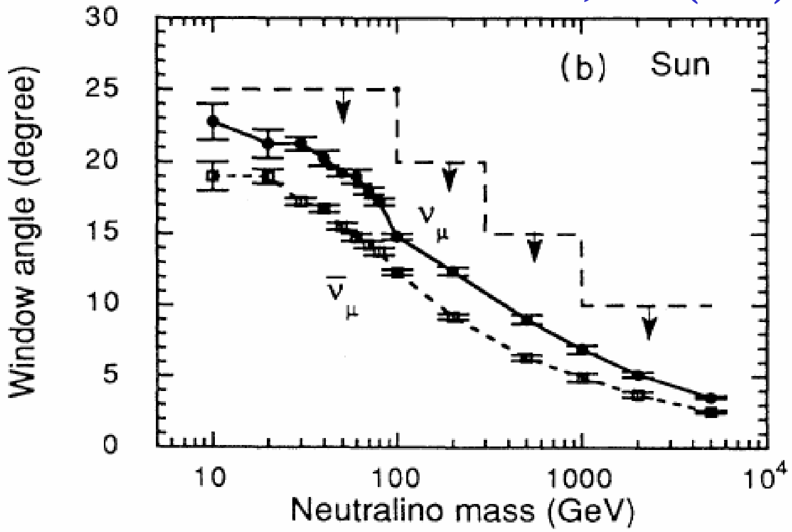
$$\beta X_0 = \ln \frac{E'_\mu + \alpha/\beta}{E_\mu + \alpha/\beta},$$

$$\Phi_\mu = \int_{E_{thr}}^{m_D} dE_\mu \frac{N_A}{\alpha + \beta E_\mu} \int_{E_\mu}^{m_D} dE_{\nu_\mu} \frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}} \times \int_{E_\mu}^{E_{\nu_\mu}} dE'_\mu \left[\frac{d\sigma^p_{\nu_\mu}(E_{\nu_\mu}, E'_\mu)}{dE'_\mu} r_p + \frac{d\sigma^n_{\nu_\mu}(E_{\nu_\mu}, E'_\mu)}{dE'_\mu} r_n \right] + (\nu_\mu \to \bar{\nu}_\mu)$$

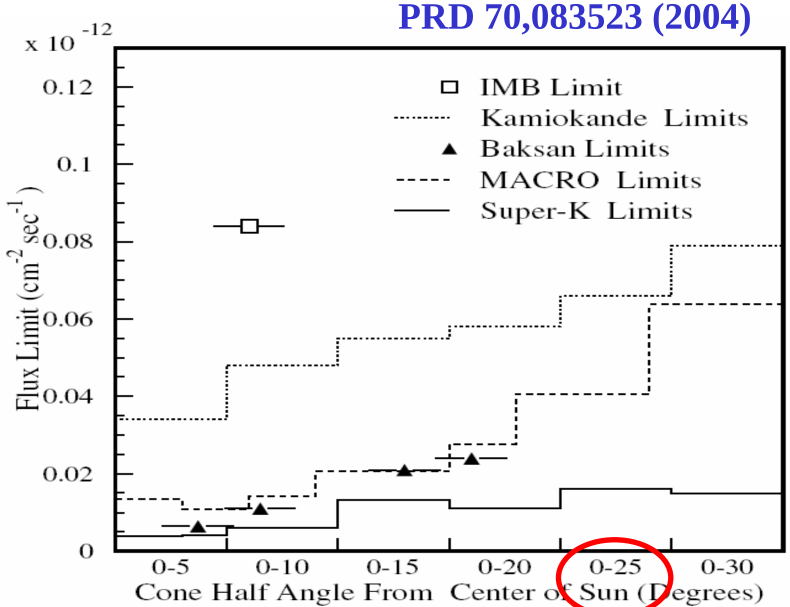
Super-K results



PRD 48, 5505 (1993)



PRD 70,083523 (2004)

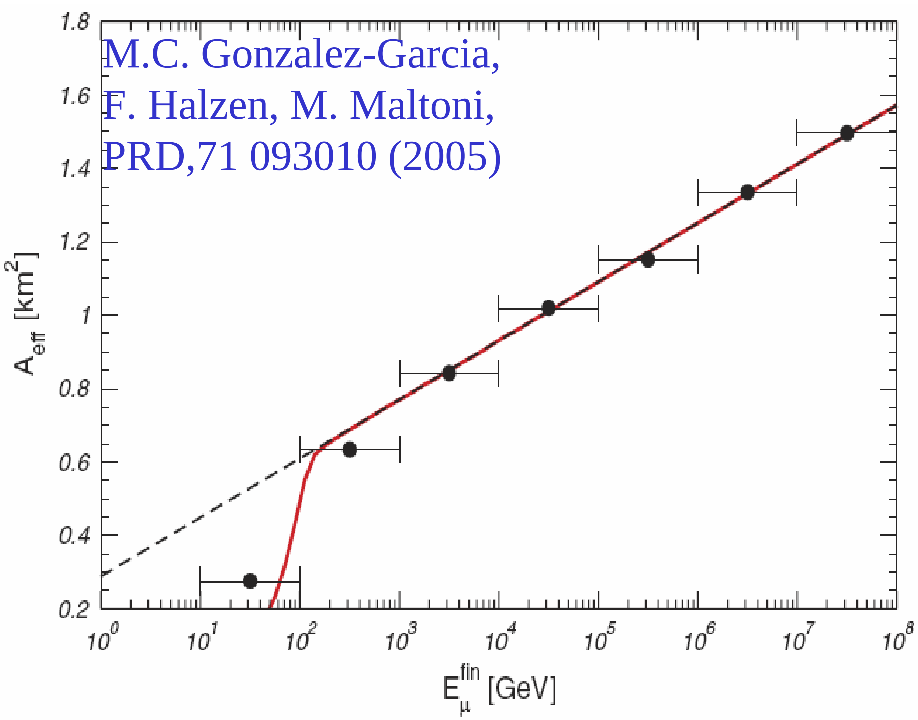


IceCube

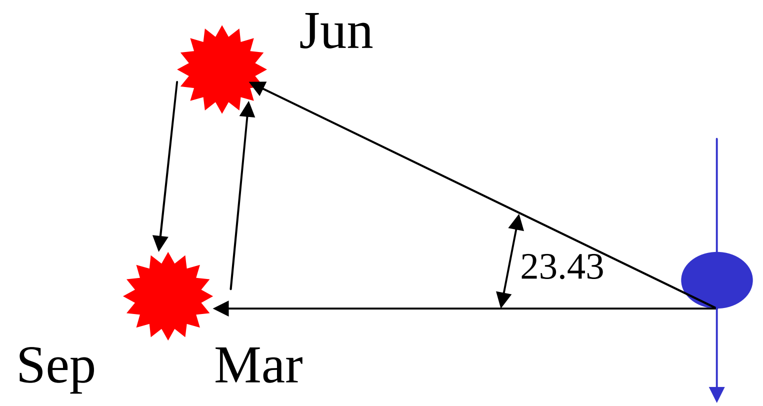
Neutrino induced upward muon numbers per year :

$$N_\mu = \int_{E_{thr}}^{m_D} dE_\mu \underline{A_{\rm eff}(E_\mu)\langle R(\cos\theta_z)\rangle} \frac{N_A}{\alpha + \beta E_\mu} \int_{E_\mu}^{m_D} dE_{\nu_\mu} \frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}} \int_{E_\mu}^{E_{\nu_\mu}} dE'_\mu \left[\frac{d\sigma^p_{\nu_\mu}(E_{\nu_\mu}, E'_\mu)}{dE'_\mu} r_p + \frac{d\sigma^n_{\nu_\mu}(E_{\nu_\mu}, E'_\mu)}{dE'_\mu} r_n \right] + (\nu_\mu \to \bar{\nu}_\mu)$$

E_{thr} = 50 GeV



$$R(\cos\theta_z) = 0.70 - 0.48\cos\theta_z \quad \text{for} \quad \theta_z > 85^\circ$$



Atmosphere Background

Atmosphere Background: $\left\langle \frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}}(\cos\theta_z)R(\cos\theta_z) \right\rangle$

TABLE XXII. ν_μ flux ($\mathrm{m^{-2}\,sec^{-1}\,sr^{-1}\,GeV^{-1}}$) above 10 GeV.

	$\cos\theta_z$										
E_ν (GeV)	1.–.9	.9–.8	.8–.7	.7–.6	.6–.5	.5–.4	.4–.3	.3–.2	.2–.1	.1–.0	*Norm*
1.000×10^1	2.557	2.625	2.703	2.799	2.911	3.052	3.232	3.482	3.824	4.172	10^{-1}
1.259×10^1	1.295	1.331	1.370	1.419	1.479	1.554	1.646	1.778	1.964	2.166	10^{-1}
1.585×10^1	0.654	0.673	0.694	0.720	0.751	0.789	0.840	0.906	1.009	1.121	10^{-1}
1.995×10^1	3.297	3.397	3.505	3.653	3.811	4.001	4.269	4.612	5.154	5.807	10^{-2}
2.512×10^1	1.659	1.710	1.770	1.848	1.930	2.033	2.167	2.349	2.627	2.997	10^{-2}
3.162×10^1	0.831	0.858	0.891	0.931	0.974	1.033	1.100	1.197	1.340	1.542	10^{-2}
3.981×10^1	4.144	4.291	4.463	4.663	4.898	5.205	5.572	6.091	6.852	7.935	10^{-3}
5.012×10^1	2.055	2.136	2.225	2.329	2.457	2.612	2.819	3.085	3.482	4.051	10^{-3}
6.310×10^1	1.014	1.056	1.104	1.161	1.228	1.308	1.420	1.556	1.762	2.059	10^{-3}
7.943×10^1	0.499	0.519	0.545	0.576	0.609	0.653	0.710	0.783	0.897	1.054	10^{-3}
1.000×10^2	2.443	2.551	2.679	2.838	3.012	3.248	3.541	3.930	4.524	5.345	10^{-4}
1.259×10^2	1.194	1.253	1.315	1.394	1.487	1.606	1.761	1.967	2.259	2.676	10^{-4}
1.585×10^2	0.583	0.611	0.643	0.684	0.732	0.790	0.869	0.979	1.129	1.338	10^{-4}
1.995×10^2	2.837	2.969	3.134	3.340	3.568	3.876	4.270	4.843	5.619	6.676	10^{-5}
2.512×10^2	1.371	1.439	1.521	1.621	1.732	1.897	2.092	2.384	2.785	3.322	10^{-5}
3.162×10^2	0.658	0.695	0.737	0.786	0.844	0.923	1.022	1.168	1.378	1.646	10^{-5}
3.981×10^2	3.146	3.328	3.547	3.792	4.096	4.482	4.988	5.700	6.771	8.124	10^{-6}
5.012×10^2	1.496	1.585	1.696	1.819	1.975	2.171	2.425	2.776	3.308	3.990	10^{-6}
6.310×10^2	0.706	0.753	0.806	0.869	0.949	1.045	1.172	1.353	1.617	1.950	10^{-6}
7.943×10^2	3.307	3.537	3.807	4.123	4.521	5.008	5.643	6.568	7.855	9.512	10^{-7}
1.000×10^3	1.535	1.643	1.781	1.940	2.133	2.386	2.708	3.167	3.796	4.634	10^{-7}
1.259×10^3	0.705	0.759	0.825	0.905	1.001	1.125	1.288	1.515	1.840	2.250	10^{-7}
1.585×10^3	0.320	0.347	0.378	0.418	0.465	0.526	0.608	0.722	0.886	1.088	10^{-7}
1.995×10^3	1.441	1.568	1.717	1.908	2.141	2.439	2.848	3.416	4.222	5.239	10^{-8}
2.512×10^3	0.643	0.702	0.775	0.861	0.973	1.119	1.318	1.597	2.007	2.511	10^{-8}
3.162×10^3	0.285	0.312	0.346	0.387	0.438	0.508	0.605	0.742	0.945	1.197	10^{-8}
3.981×10^3	1.251	1.375	1.530	1.724	1.965	2.286	2.757	3.422	4.400	5.675	10^{-9}
5.012×10^3	0.548	0.602	0.675	0.759	0.878	1.024	1.243	1.553	2.047	2.670	10^{-9}
6.310×10^3	0.238	0.264	0.296	0.335	0.389	0.457	0.556	0.706	0.944	1.237	10^{-9}
7.943×10^3	1.032	1.156	1.284	1.473	1.694	2.021	2.466	3.196	4.304	5.676	10^{-10}
1.000×10^4	0.444	0.497	0.556	0.635	0.732	0.882	1.079	1.410	1.946	2.615	10^{-10}

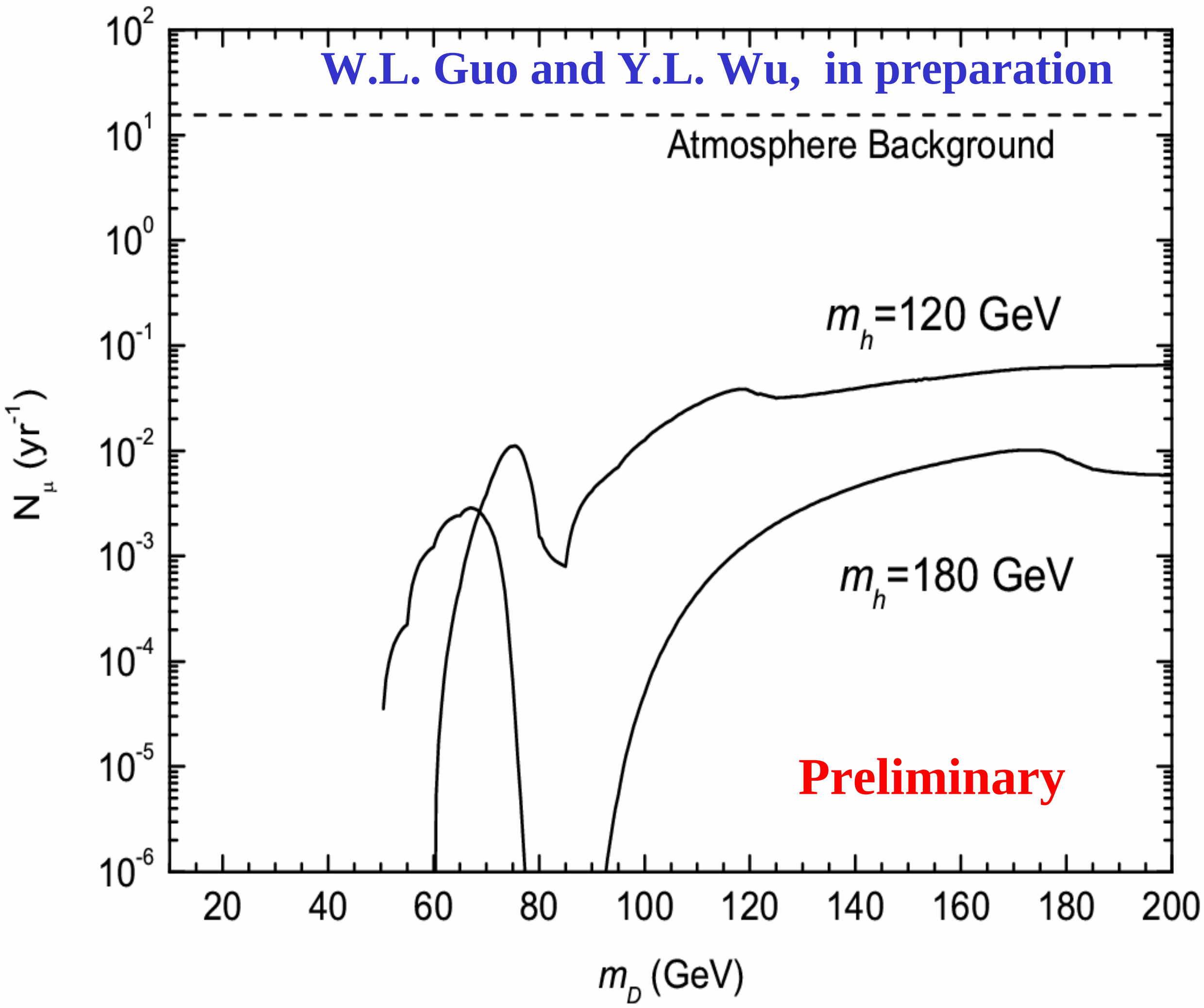
M. Honda, et. al, PRD 75,043006 (2007)

Take half-angle to be 2 degree!

Liu, Yin and Zhu, PRD 77, 115014 (2008)

***E_\mu* from 50 to 200 GeV**

IceCube results



Summary

- In the simplest DM model, the DM direct search experiments can exclude two regions; the DM indirect search experiment PAMELA can exclude a very narrow region.
- In the 2HBLR, the predicted direct detection cross section depends on the Higgs mixing and Yukawa couplings. However, the indirect detection cross section is independent of the above two factors.
- The neutrino signals from the DM annihilation in the Sun are far less than the upper bound in the Super-K and the atmosphere background in the IceCube.

Thanks !