Constraints on Dark Matter Parameters From Direct Searches

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Introduction

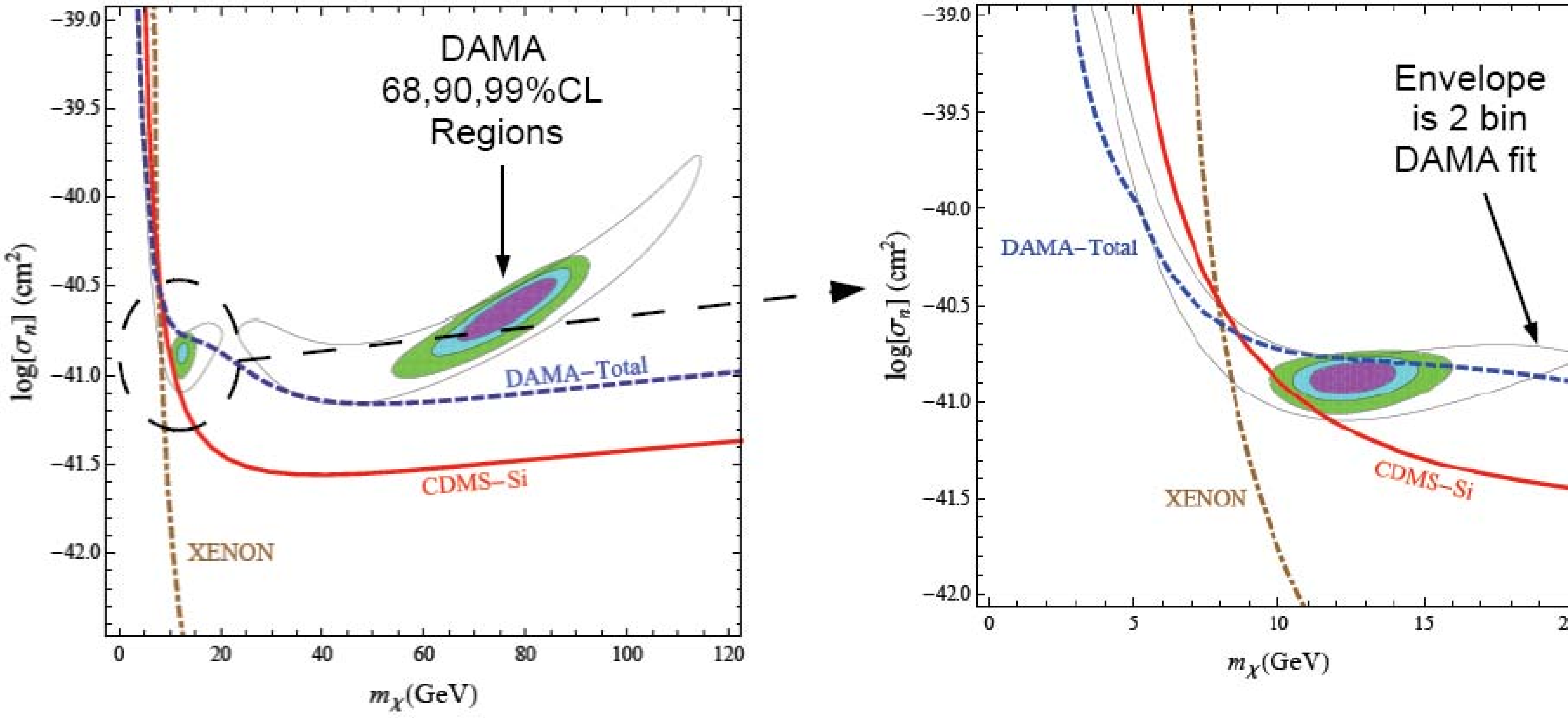
If dark matter exist, better can be detected directly on earth bound detectors.

Direct detection: typical recoil energy around 50 KeV. (Dama, …)

Indirect detection: Gamma-ray from annihilation of dark matter in the galactic halo, center of the Sun and other sources and …

LDM Plots

SC, Pierce, We


DAMA
68,90,99%CL
Regions

Envelope
is 2 bin
DAMA fit

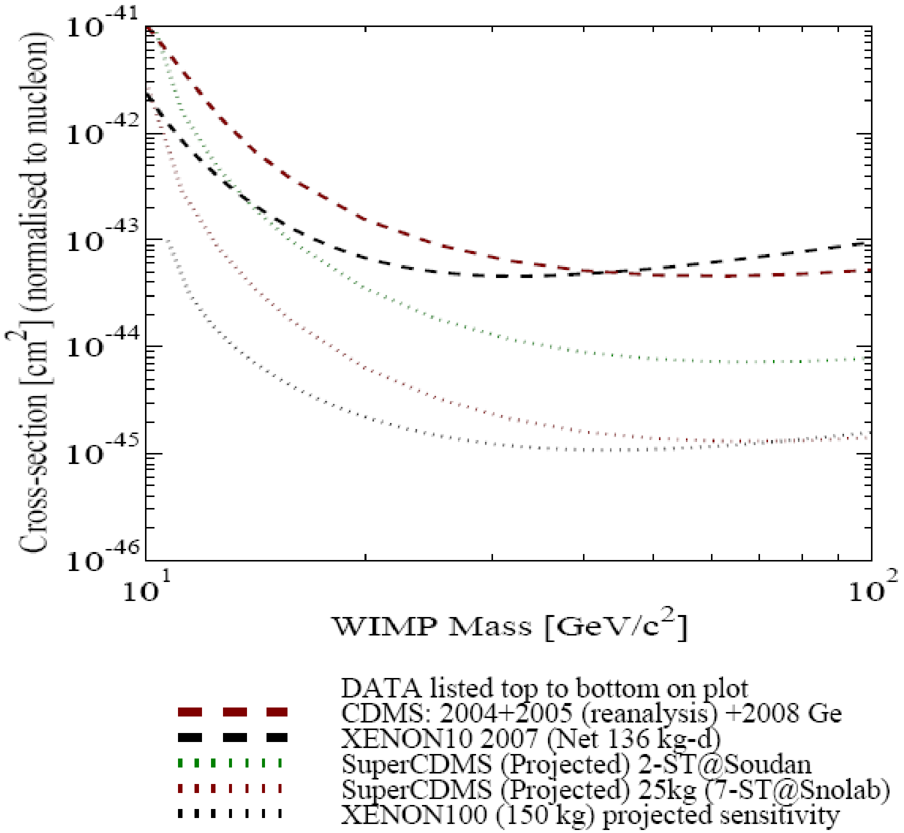
Spectral information disfavors m < 10 GeV
Need nonstandard astrophysics/expt'l issues for consistency

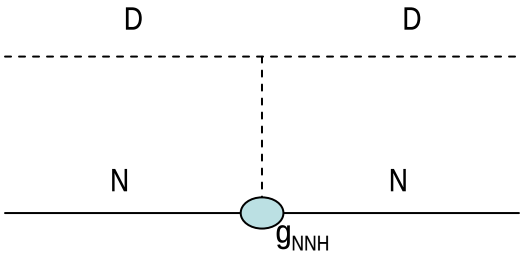
- The current and projected experimental upper limits of spin-independent WIMP-nucleon elastic cross-section as a function of WIMP mass are shown in the right figure.

  Maximal recoil kinetic energy:

  Kn = Kd [4Mn Md/(Mn+Md)^2]

- The effective dark matter coupling is needed for elastic darkon-nucleon cross section calculation.





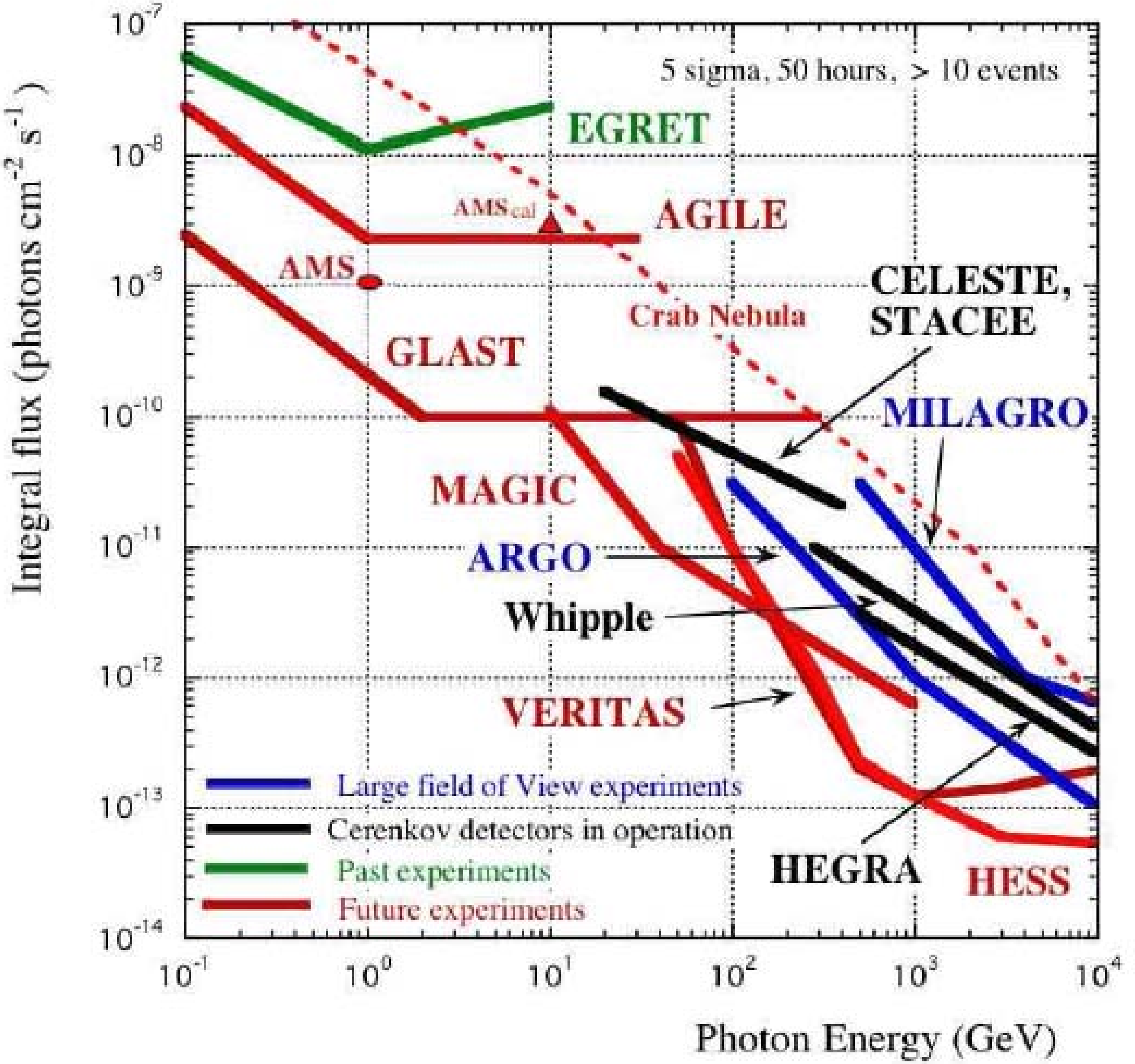


Figure 18: Sensitivity of present and future detectors in gamma-ray astrophysics (from Ref. [386]).

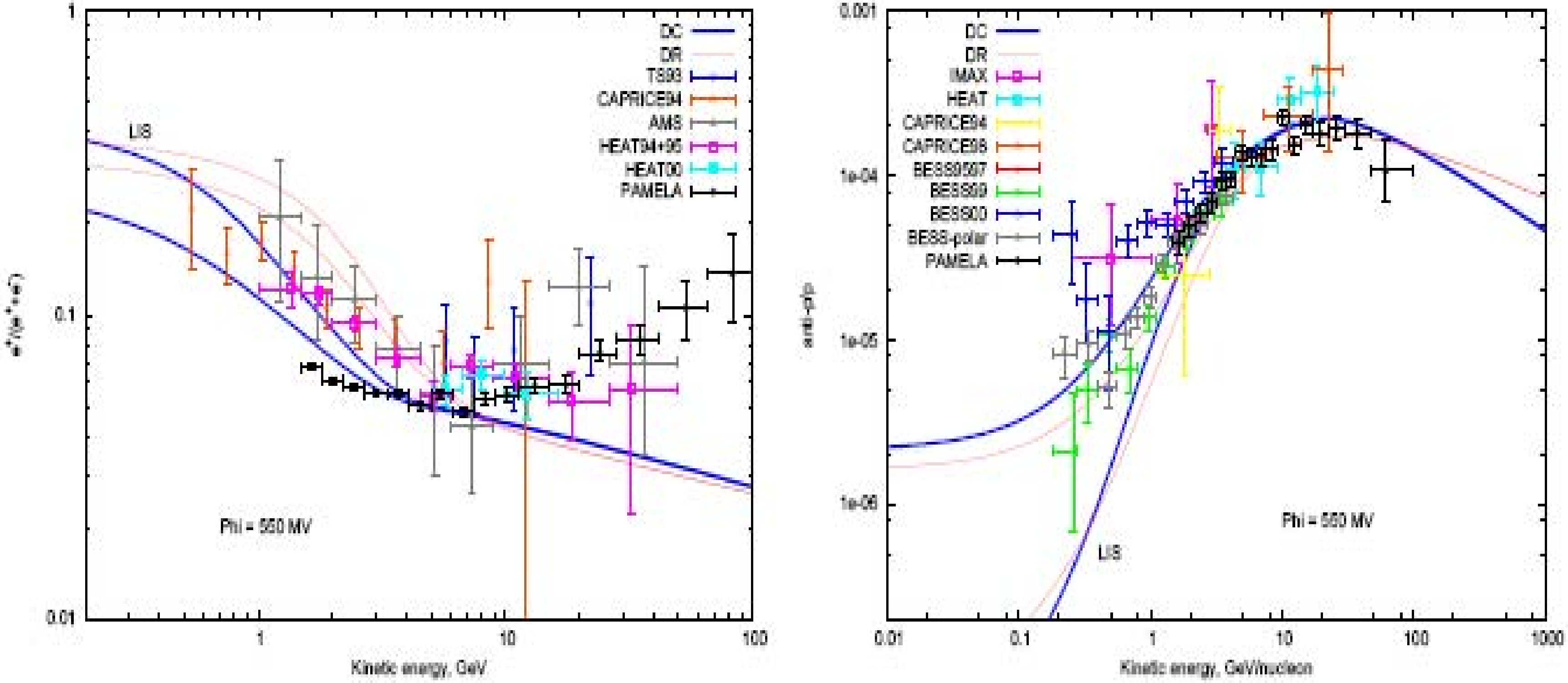


FIG. 2: Left: the calculated positron fraction compared with observations; right: $\bar{p}/p$ ratio. References of the observational data are, positron fraction: TS93[64], CAPRICE94[60], AMS[7], HEAT94+95[6], HEAT00[65], PAMELA[5]; $\bar{p}/p$: IMAX[66], HEAT[67], CAPRICE94[68], CAPRICE98[69], BESS95+97[70], BESS99[71], BESS00[71], BESS-polar[72], PAMELA[4].

Many weakly interacting massive particle (WIMP) models are proposed, e.g. SUSY, …

But dark matter identity and property are still not known.

We focus on a real SM gauge singlet scalar field first proposed by

V. Silveira and A. Zee (1985) which is simplest model with a WIMP candidate.

Relic Density Abundance

- Thermal relic density can be calculated by standard big-bang cosmology (E.W.Kolb and M.Turner)

$$\Omega_D h^2 \approx \frac{1.07 \times 10^9 x_f}{\sqrt{g_*} m_{pl} \mathrm{GeV} \langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle}, \quad x_f \approx \ln \frac{0.038 m_{pl} m_D \langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle}{\sqrt{g_* x_f}},$$

Ω_D is the cold dark matter energy density fraction of the universe

h is the Hubble constant in units of 100 km/(s Mpc)

g_* is the relativistic degrees of freedom with mass less than T_f

$m_{pl} = 1.22 \times 10^{19}$ GeV Plank mass

m_D WIMP mass

T_f freeze out temperature

$x_f = m_D/T_f$ inverse freeze-out temperature in unit of m_D

- $\Omega_D h^2 = 0.105(8)$ cold dark matter relic by PDG

Standard Model + Darkon

Darkon + Standard Model

- Restricted by renormalizability and dark matter requirement: L(SM) + L(D)

$$L = \frac{\lambda_D}{4} D^4 + \frac{1}{2}\left(m_0^2 + \lambda v^2\right) D^2 + \frac{1}{2}\lambda h^2 D^2 + \underline{\lambda v h D^2}$$

$v = 246\ \mathrm{GeV}$

m_D

Interact with SM through Higgs

- This simplest model with a WIMP candidate has
  → only one scalar singlet added, and
  → other SM interactions remains intact.
- To play a role of cold dark matter
  stable → Z_2 symmetry to annihilate in pairs,
  weakly interact → no VEV to decay like Higgs, couple to Higgs only
  relic → determine Darkon-Higgs coupling < 1 if calculating perturbatively

Annihilation Rate in SM+D

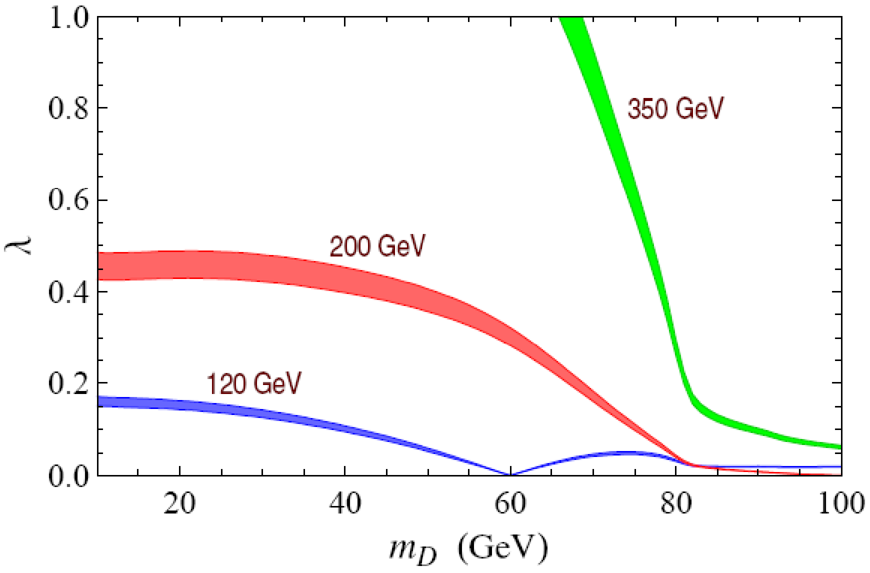
- Annihilation rate can be calculated according to the formula

$$\sigma_{\rm ann}\, v_{\rm rel} = \frac{8\lambda^2 v^2}{\left(4m_D^2 - m_h^2\right)^2 + \Gamma_h^2\, m_h^2}\, \frac{\sum_i \Gamma(\tilde{h} \to X_i)}{2m_D} \qquad \sqrt{s} = 2m_D$$

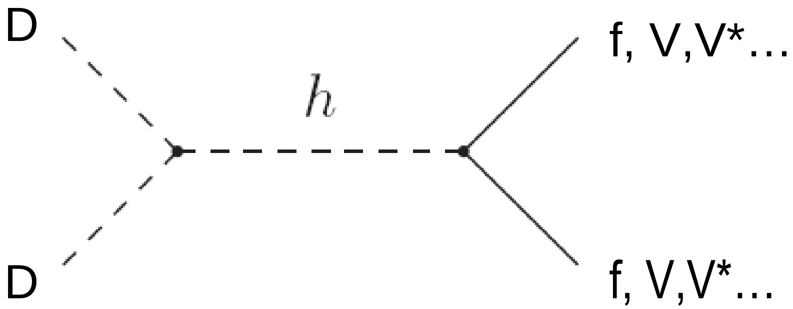
$\tilde{h}$ is a virtual with mass $2m_D$

$$v_{\rm rel} = 2|\boldsymbol{p}_D^{\rm cm}|/m_D$$

- The coupling λ can be determined by relic abundance constraint
- Other effects of Darkon can be known and probed,



e.g. Darkon-Nucleon Scattering

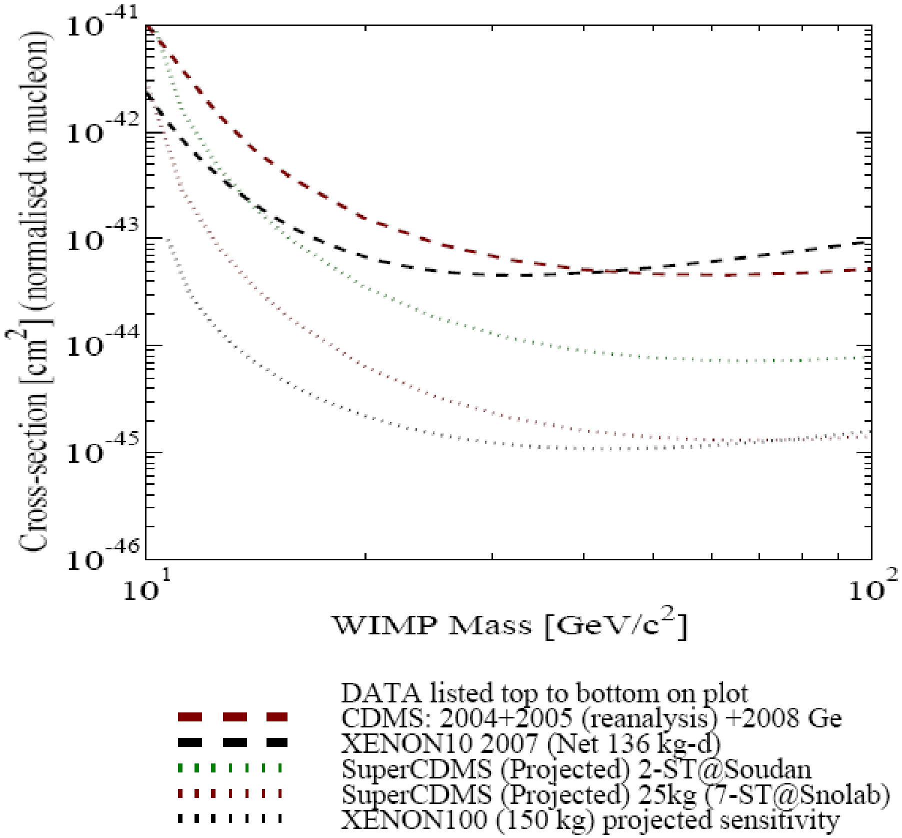


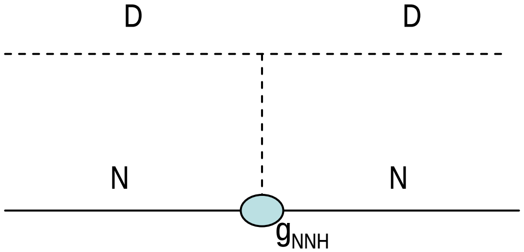
Direct Dark Matter Searches

Dark Matter Direct Search Experiment

- ♦ The current and projected experimental upper limits of spin-independent WIMP-nucleon elastic cross-section as a function of WIMP mass are shown in the right figure.

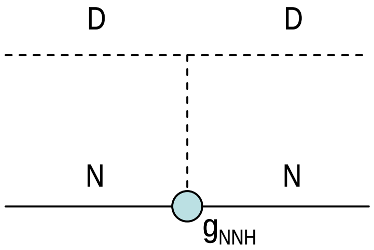
- ♦ The effective darkon-higgs coupling is needed for elastic darkon-nucleon cross section calculation.





$$\sigma_{\rm el}^{\rm SM} \simeq \frac{\lambda^2 \, g_{NNh}^2 \, v^2 \, m_N^2}{\pi \, (m_D + m_N)^2 \, m_h^4}$$

Effective Higgs-Nucleon Coupling



- Generic Yukawa couplings

$$\mathcal{L}_{qq\mathcal{H}} = -\sum_q \frac{k_q}{v} m_q \bar{q}q\,\mathcal{H}$$

- It's simpler

$$g_{NN\mathcal{H}}\,\bar{N}N = \langle N|\frac{k_u}{v}(m_u\,\bar{u}u + m_c\,\bar{c}c + m_t\,\bar{t}t) + \frac{k_d}{v}(m_d\,\bar{d}d + m_s\,\bar{s}s + m_b\,\bar{b}b)|N\rangle$$

for SM $k_u^{SM} = k_d^{SM} = 1$ and THDM II $k_u^h = \frac{\cos\alpha}{\sin\beta}\,, k_d^h = -\frac{\sin\alpha}{\cos\beta}\,,\qquad k_u^H = \frac{\sin\alpha}{\sin\beta}\,, k_d^H = \frac{\cos\alpha}{\cos\beta}$

- The recoil energy of nuclei is low < 100keV

  we can use chiral Lagrangian method to obtain the effective coupling as

$$g_{NN\mathcal{H}} = (k_u - k_d)\frac{\sigma_{\pi N}}{2v} + k_d\,\frac{m_N}{v} + \frac{4k_u - 25k_d}{27}\,\frac{m_B}{v}$$

m_B is the baryon mass in the chiral limit, m_N is the physical mass of nucleon

- Numerically we adopt $\sigma_{\pi N} = 45\,\mathrm{MeV}$ and obtain the coupling as

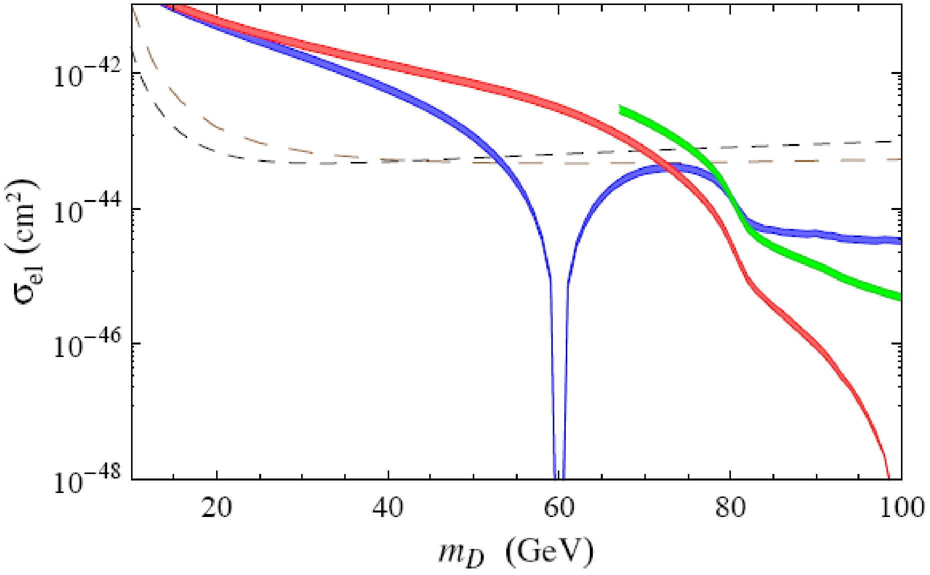
$$g_{NN\mathcal{H}} \simeq (1.217\,k_d + 0.493\,k_u) \times 10^{-3}$$

SM+D on Experiment

- SM+D with Darkon mass in the range of 10~(50 ,70, 80) GeV at Higgs mass (120, 200, 350) is ruled out by upper limit 90% curves of XENON10 2007 and CDMSII 2008.

- This makes the possibility of Darkon as a potential explanation of the gamma ray excess observed by EGRET, and positron excess observed by PAMELA difficult, which compatible with a dark matter with a mass in the range of 50 to 70 GeV

- We show that by extending SM+D to two Higgs doublet model II plus a darkon (THDMII+D), the experimental constraint from spin independent WIMP-nucleon elastic scattering cross section can be circumvented due to a cancellation.



Two Higgs Doublet Model II
+ Darkon

Two Higgs Doublet Model II + D

Darkon Lagrangian in THDM+D are by an analogy to SM+D argument

$$-\mathcal{L}_D = \frac{\lambda_D}{4} D^4 + \frac{m_0^2}{2} D^2 + D^2 (\lambda_1 H_1^\dagger H_1 + \lambda_2 H_2^\dagger H_2 \ ).$$

Writing the Higgs field in component form, we have

$$H_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} h_i^+ \\ v_i + h_i + i I_i \end{pmatrix}.$$

The fields h_i^+, and I_i can be expressed in terms of physical Higgs H^+, A and the would-be goldstone bosons w and z are given by

$$\begin{pmatrix} h_1^+ \\ h_2^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} w^+ \\ H^+ \end{pmatrix}, \quad \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} z \\ A \end{pmatrix}.$$

Here $\tan\beta = v_2/v_1$.

The neutral scalar Higgs h_i can be expressed in terms of mass eigenstates H and h

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}.$$

Darkon Mass and Couplings

- ♣ Darkon terms with of physical degree of freedom

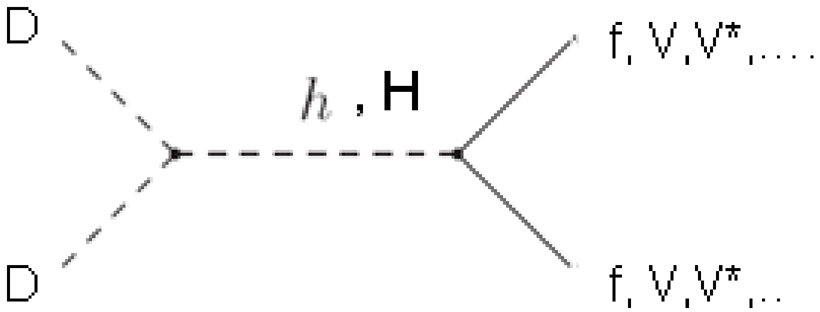
$$m_D^2 = m_0^2 + v^2(\lambda_1 \cos^2\beta + \lambda_2 \sin^2\beta + 2\lambda_3 \cos\beta \sin\beta),$$

$$-L_{hD^2} = (-\lambda_1 \cos\beta \sin\alpha + \lambda_2 \sin\beta \cos\alpha \quad)vhD^2 = \lambda_h vhD^2,$$

$$-L_{HD^2} = v(\lambda_1 \cos\beta \cos\alpha + \lambda_2 \sin\beta \sin\alpha \ ) = \lambda_H vHD^2,$$

-- there is no AD^2 couplings.

-- since $m_0, \lambda_1, \lambda_2$ are free parameters we can treat $m_D, \lambda_h, \lambda_H$ as new free parameters



Two Higgs Doublet Models

- ♣ There are tree types of THDM which distinguished by Yukawa couplings
- ♣ THDM type I -- second doublet couples to two isospin sectors, unchangable (being fixed, like SM+D)

$$L_Y^I = -\bar{Q}_L \lambda_2^u \tilde{H}_2 U_R - \bar{Q}_L \lambda_2^d H_2 D_R - \bar{L}_L \lambda_2^l H_2 E_R + H.C.$$

$$\tilde{H}_i = i\tau_2 H_i^*$$

- ♣ THDM type II – second Higgs to up and first to down sector

$$L_Y^{II} = -\bar{Q}_L \lambda_2^u \tilde{H}_2 U_R - \bar{Q}_L \lambda_1^d H_1 D_R - \bar{L}_L \lambda_1^l H_1 E_R + H.C.$$

- ♣ THDM type III, too many parameters and FCNC

$$\begin{aligned} L_Y^{III} = & -\bar{Q}_L \lambda_1^u \tilde{H}_1 U_R - \bar{Q}_L \lambda_2^u \tilde{H}_2 U_R - \bar{Q}_L \lambda_1^d H_1 D_R - \bar{Q}_L \lambda_2^d H_2 D_R \\ & -\bar{L}_L \lambda_1^l H_1 E_R - \bar{L}_L \lambda_2^l H_2 E_R + H.C. \end{aligned}$$

- ♣ So we consider THDM II only

Yukawa Couplings

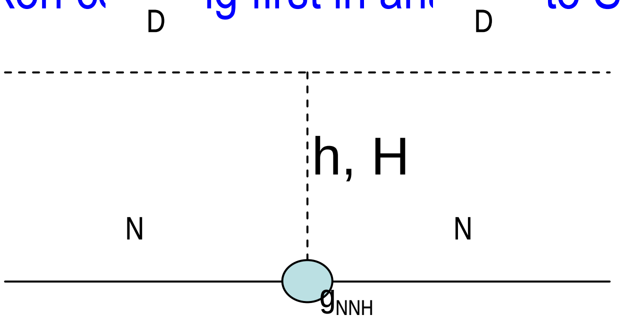
- The Yukawa couplings of THDM II are

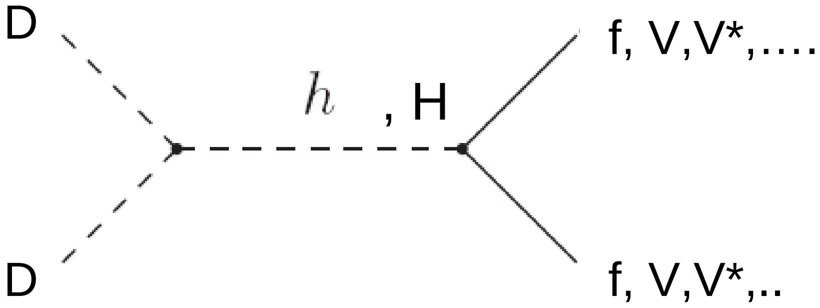
$$\begin{aligned} L_{hff} &= -\bar{U}_L M^u U_R\left(\frac{\cos\alpha}{v\sin\beta}h+\frac{\sin\alpha}{v\sin\beta}H\right)-\bar{D}_L M^d D_R\left(-\frac{\sin\alpha}{v\cos\beta}h+\frac{\cos\alpha}{v\cos\beta}H\right)\\ &\quad -\bar{E}_L M^l E_R\left(-\frac{\sin\alpha}{v\cos\beta}h+\frac{\cos\alpha}{v\cos\beta}H\right)+H.C. \end{aligned}$$

- The ks can be read as

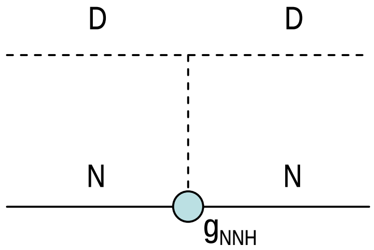
$$k_u^h = \frac{\cos\alpha}{\sin\beta}\,, k_d^h = -\frac{\sin\alpha}{\cos\beta}\,, \qquad k_u^H = \frac{\sin\alpha}{\sin\beta}\,, k_d^H = \frac{\cos\alpha}{\cos\beta}$$

- With Yukawa couplings needed the s-channel annihilation rate can be calculated with quark degrees of freedom
- And the t-channel elastic cross section can also be calculated by inferring effect Higgs-darkon c ng first in an to SM+D





DN-DN Elastic Scattering



- ♣ Elastic scattering formula in THDM II +D

$$\sigma_{el-SI}^{THDM+D}(DN \to DN) = \frac{m_N^2}{\pi(m_N+m_D)^2}\left|\frac{\lambda_h \cdot v \cdot g_{NNh}^{THDM}}{m_h^2} + \frac{\lambda_H \cdot v \cdot g_{NNH}^{THDM}}{m_H^2}\right|^2$$

- ♣ Coupling is modified by

$$g_{NN\mathcal{H}}^{THDM} = (k_u^{\mathcal{H}} - k_d^{\mathcal{H}})\frac{\sigma_{\pi N}}{2v} + k_d^{\mathcal{H}}\frac{m_N}{v} + \frac{4k_u^{\mathcal{H}} - 25k_d^{\mathcal{H}}}{27}\frac{m_B}{v}$$

- ♣ k's in THDM II are

$$k_u^h = \frac{\cos\alpha}{\sin\beta}\,,\ k_d^h = -\frac{\sin\alpha}{\cos\beta}\,, \qquad k_u^H = \frac{\sin\alpha}{\sin\beta}\,,\ k_d^H = \frac{\cos\alpha}{\cos\beta}\,.$$

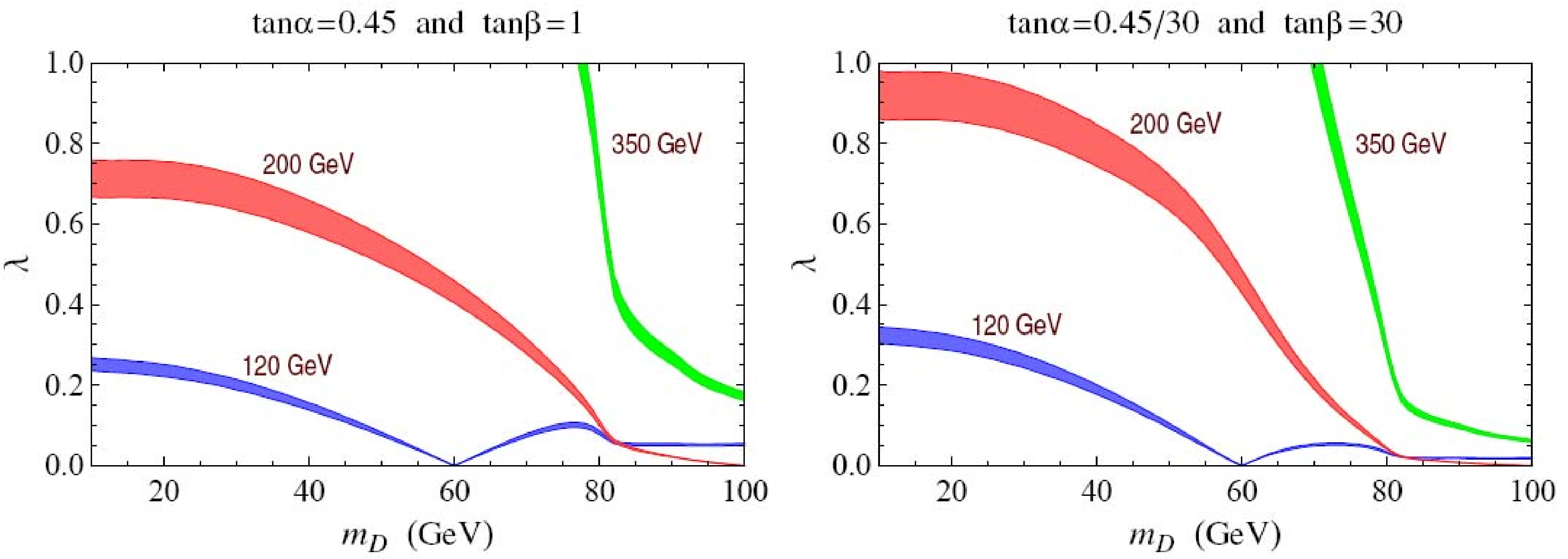
- ♣ If only light Higgs contribute (for small λ_H or large m_H) ,

$$\sigma_{el-SI}^{THDM+D}(DN \to DN) = \frac{m_N^2}{\pi(m_N+m_D)^2}\left|\frac{\lambda_h \cdot v \cdot g_{NNh}^{THDM}}{m_h^2}\right|^2$$

- ♣ Coupling can vanish at $\tan\alpha \tan\beta = 0.405$

Darkon Couplings Result

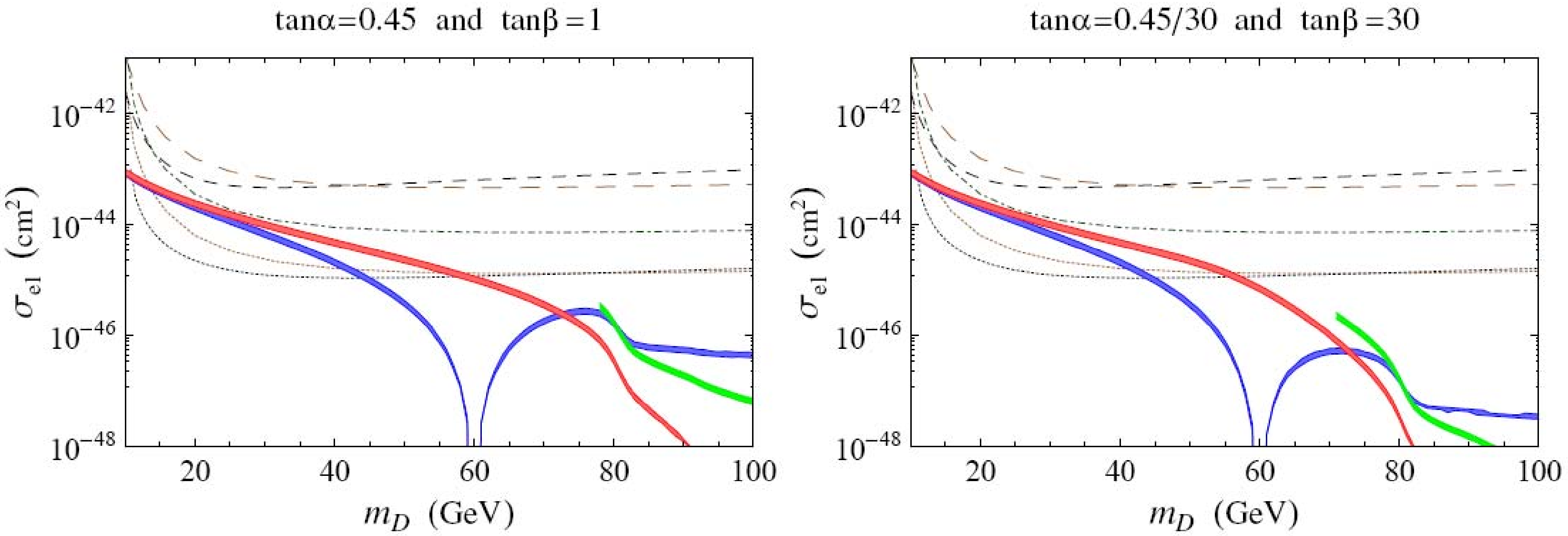
- For partial cancellation in THDMII+D ---
  the allowed coupling with different Higgs mass and $\tan\beta$ are shown
- A lager virtual Higgs decay width implies a smaller lambda, e.g. poles of Darkon mass = ½ Higgs mass



Allowed ranges of λ in the 2HDMII+D.

DN-DN Elastic Result

- ♣ This partial cancellation in THDMII+D can escape from the XENON10 2007 and CDMSII 2008 constraints.



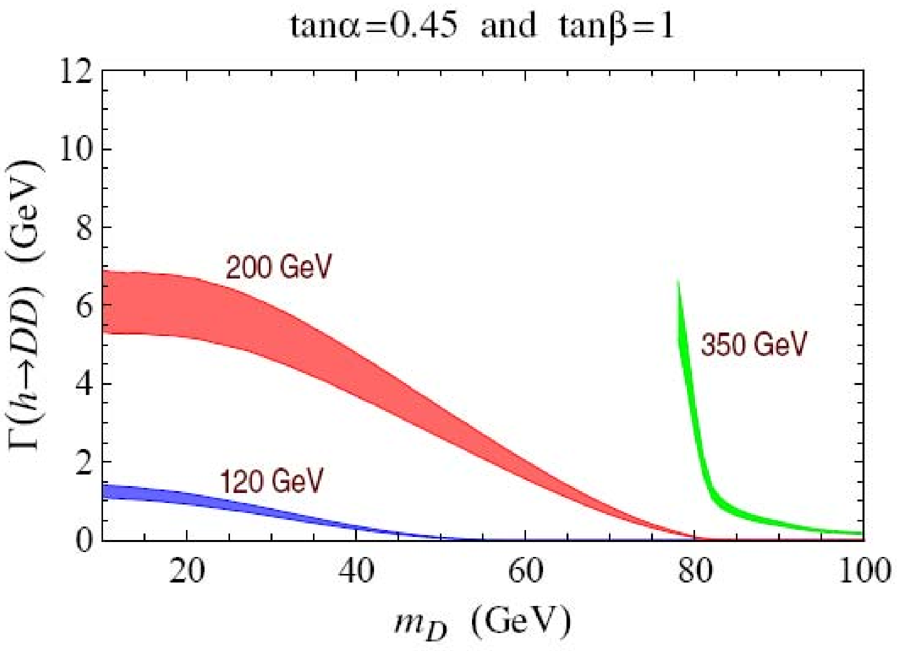
The black (brown) dashed curve indicates the upper limit found by XENON10 (CDMS). The purple, black, and brown dotted curves are the projected sensitivities of SuperCDMS at Soudan, SuperCDMS at Snolab, and XENON100.

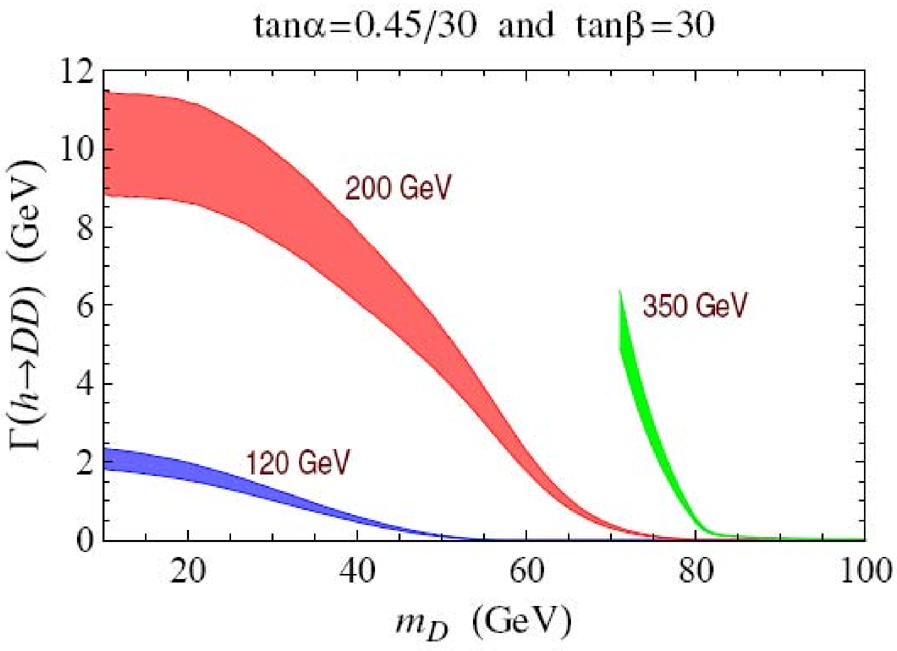
- ♣ Future XENON100 2009 and SuperCDMS experiments can offer more stringent constraints

Discussions and Conclusions

Discussions -- Implications

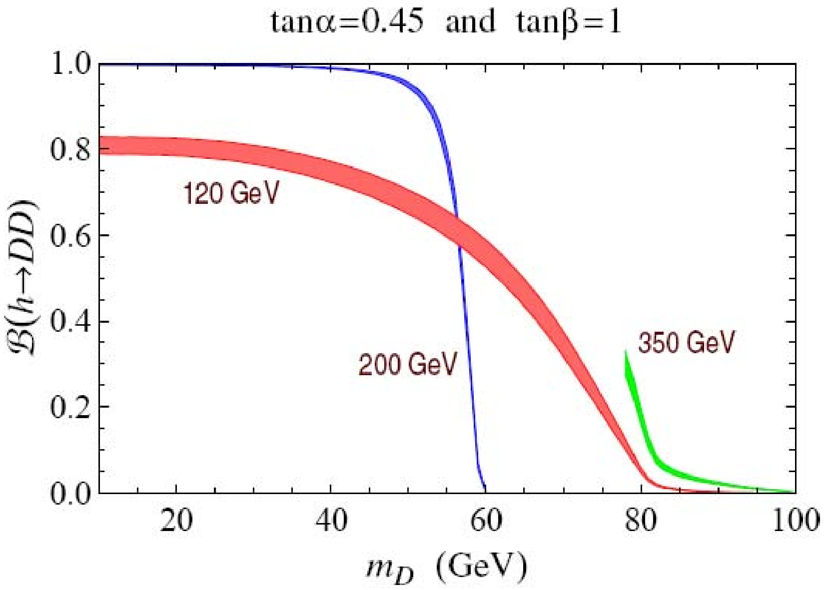
- We see that for small *mD*, $h \rightarrow DD$ dominate the decay, being stable so invisible. Make excluded Higgs search harder.
- The total decay width is increased considerably to make resonance reconstruction more difficult.
- The increasing of the invisible width of Higgs boson can be compared with the SM prediction to probe Darkon.
- Large *mD* the $h \rightarrow DD$ contribution become small and the Higgs decay is more SM like.

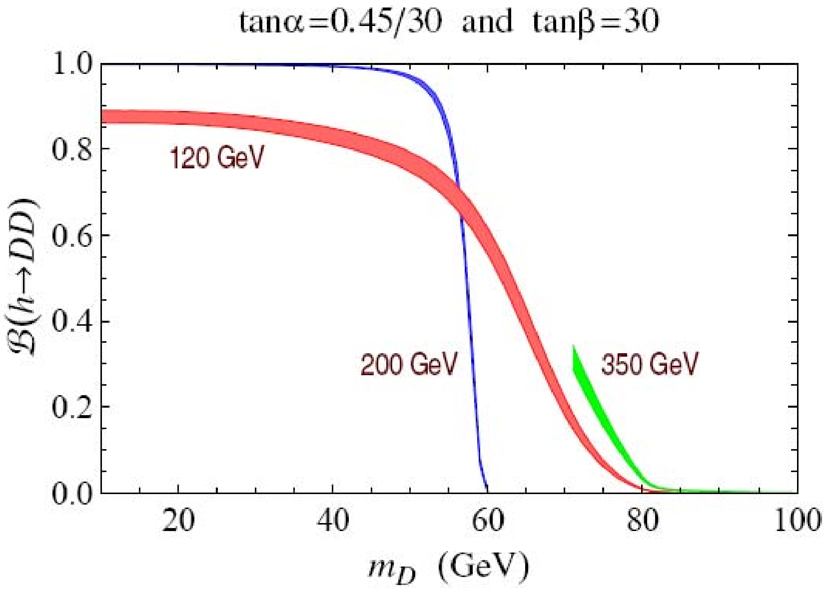




Discussions -- Implications

- With large invisible branching ratio, search of Higgs at CMS may be difficult, but at ALTLAS invisible Higgs decay signal can be studied by looking for missing energy of the Higgs decay from weak boson fusion processes.
- Darkon can be probed by compare to the SM invisible Higgs decay prediction at LHC.
- Invisible branching ratio between 0.3 to 0.6 with $m_h > 160$ GeV can be studied even with 30*fb*^-1 at ALTLAS.
- With 300*fb^-1*, if Higgs mass is larger than 2*mZ*, say *mh* = 300 GeV, at ATLAS, the total width can be determined to an accuracy of 10% ..





Conclusions

- ♠ SM+D with Darkon mass in the range of 10~(50 ,70, 80) GeV at Higgs mass (120, 200, 350) is ruled out by XENON10 and CDMSII 2008.
- ♠ THDM II+D can have cancelation with Higgs-Nucleon coupling.

- ♠ The Darkon mass region in SM+D excluded by XENON10 and CDMSII 2008 can be restored in THDM II+D extension.
- ♠ The future Experiments XENON100 and SuperCDMS can set stringer constraints.
- ♠ Darkon dominate Higgs invisible width is implied and can be probed through missing energy processes at LHC.