Singlet-Doublet Dark Matter

(or “What can near term experiments tell us about the WIMP miracle?”)

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(SLAC)

with Jack Kearney, Aaron Pierce, and David Tucker-Smith

arXiv:1109.2604

Rutgers New High Energy Theory Center Seminar
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What is Dark Matter?

- We have evidence from
  - The rotation curves of galaxies,
  - The spectrum of the cosmic microwave background,
  - Gravitational lensing,
  - The "bullet cluster" observation,

  that ~ 80% of the matter in the Universe is "dark."

  (For a discussion of "how dark?" see Zurek, McDermott, Yu [arXiv:1011.2907])

- This is typically stated as a relic density

$$\Omega_{\rm DM} h^2 = 0.1123 \pm 0.0035$$ (WMAP7 [arXiv:1001.4538])

- Note that since that since dark matter is still around today, it must be stable (on cosmological time scales).

What can we know about Dark Matter?

Early Universe Interactions with the SM: set the relic density

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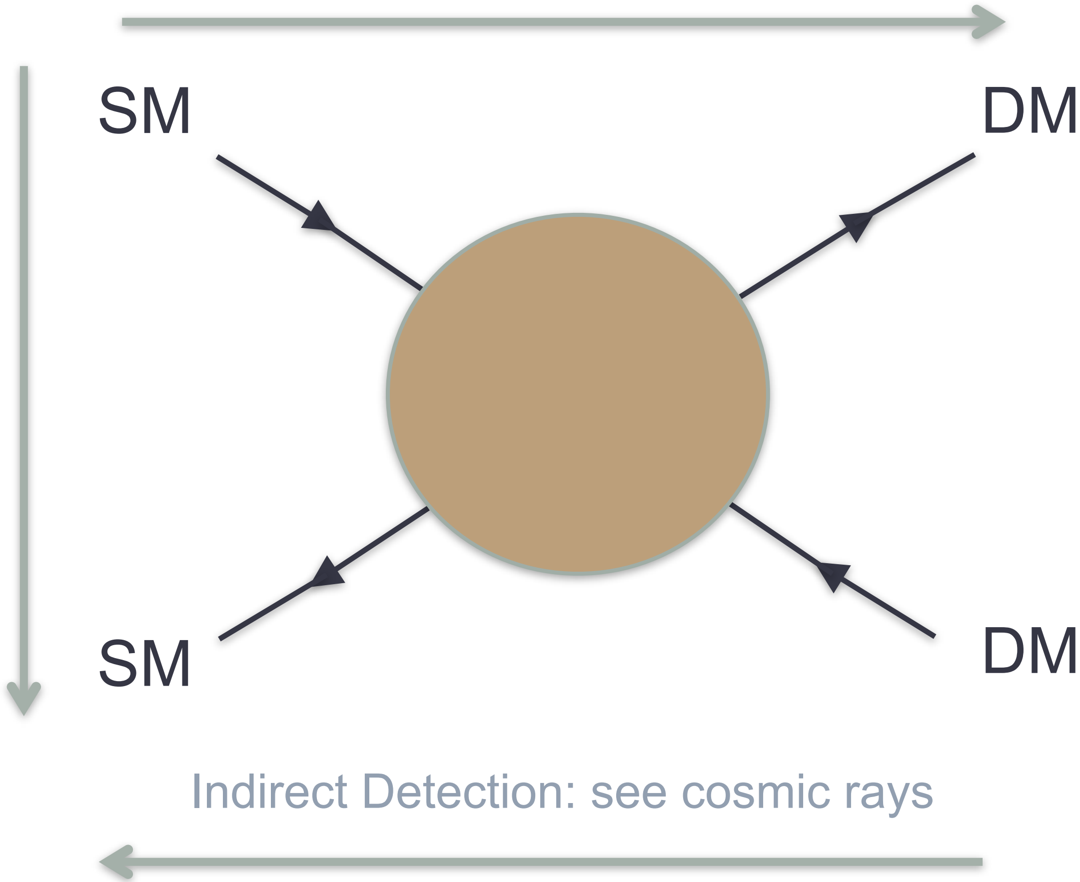
Early Universe

Interactions with the SM: set the relic density

Today

Production: signal at colliders

Direct Detection: see nuclear recoils



Indirect Detection: see cosmic rays

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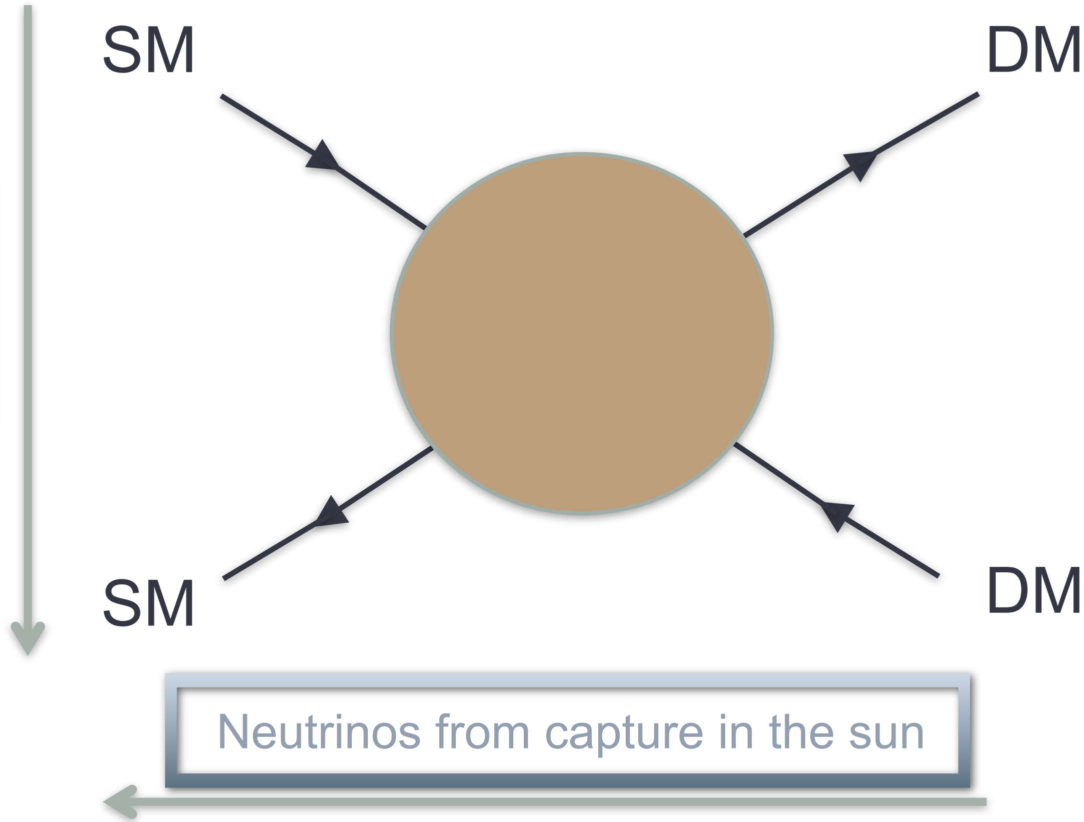
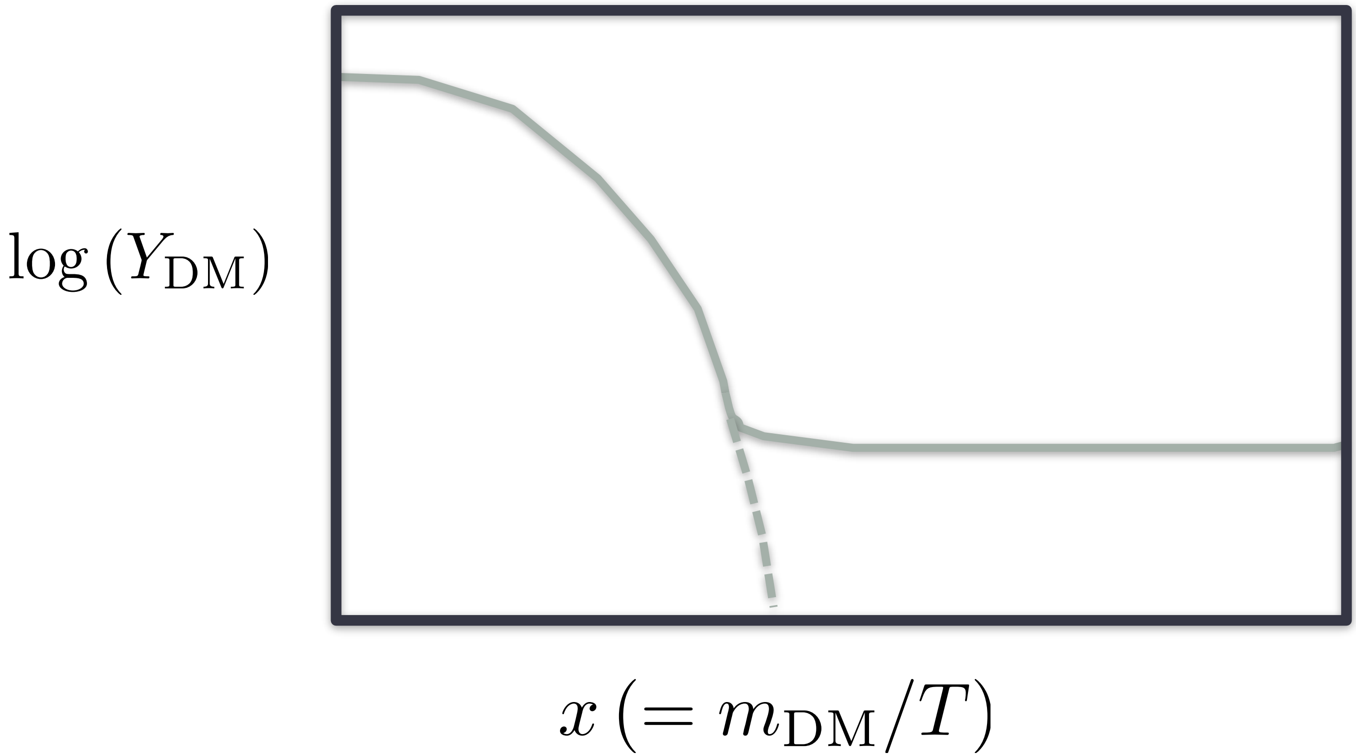


Neutrinos from capture in the sun

Thermal Dark Matter

- At the end of inflation, the universe reheats.
  - The standard model and dark matter states follow equilibrium distributions.
  - Then the dark matter "freezes out" when $H(T_{fo}) \simeq \Gamma_{\text{ann}}$.



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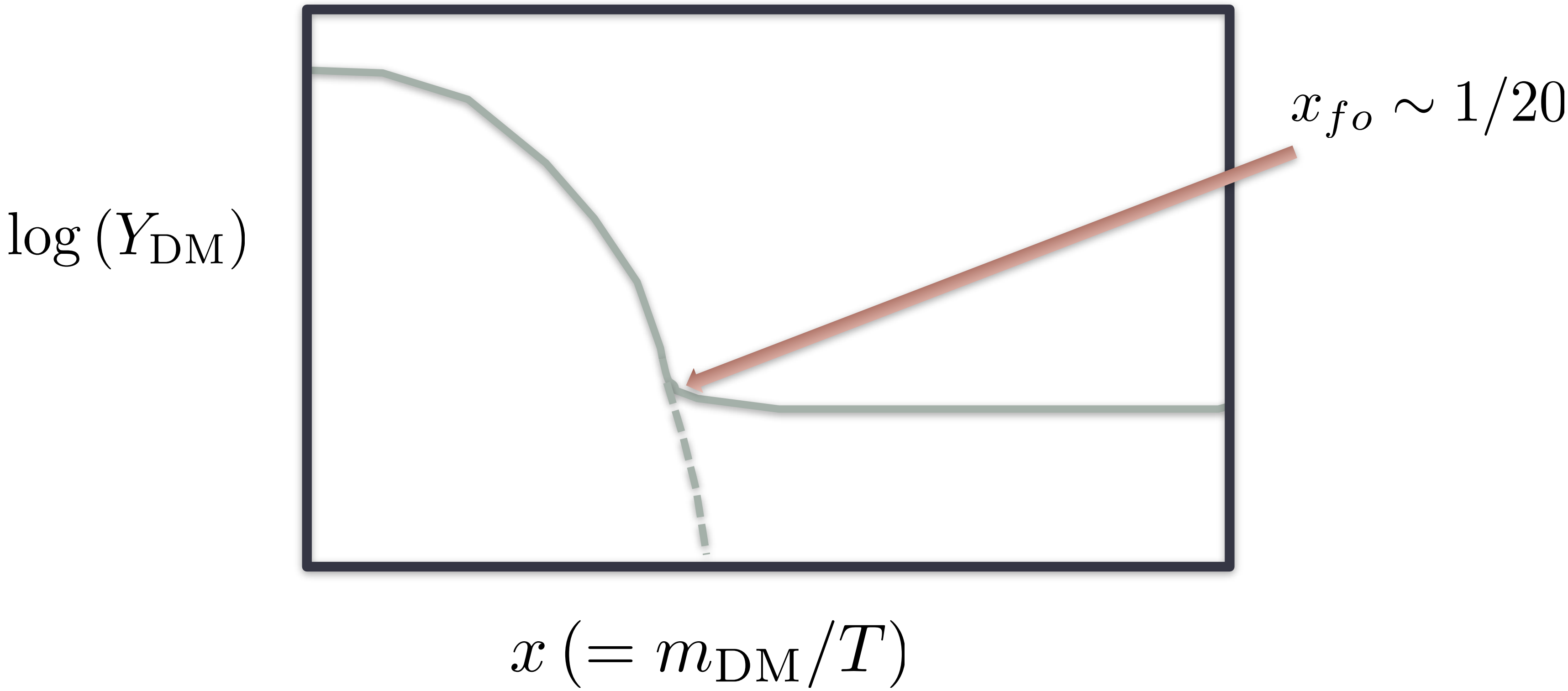

The "WIMP Miracle"

- By solving the Boltzmann equations for the thermal scenario one finds

$$\Omega_{\rm DM} h^2 \simeq 0.1 \left(\frac{3\times 10^{-26}\ {\rm cm}^3/{\rm s}}{\langle \sigma_{\rm ann} v \rangle} \right)$$

- A simple estimate yields (assuming s-wave annihilation)

$$\langle \sigma_{\rm ann} v \rangle \sim \frac{g^4}{16\pi^2} \frac{1}{M^2}$$

- If the dark matter interacts via the weak force,

$$\begin{aligned} g &= g_W \\ M &= m_W \end{aligned} \quad \Rightarrow \langle \sigma_{\rm ann} v \rangle \sim 3 \times 10^{-26} {\rm cm}^3/{\rm s}$$

Strictly Weakly Interacting

- We are interested in models where the relic density is set by *only* weak interactions.
- This occurs in the minimal supersymmetric standard model in the "well-tempered" scenario (a.k.a. the "focus point" of MSUGRA with decoupled squarks). (Arkani-Hamed, Delgado, Giudice [arXiv:hep-ph/0601041])
  - The dark matter is the lightest neutralino which is a non-trivial admixture of the Bino and/or Wino and the Higgsinos.
  - The relic density is set by annihilation to W^+W^-.
  - The coupling to the W bosons implies non-zero coupling to the quarks via either Higgs or Z boson exchange.
  - There are near term observable direct detection signals for the majority of the parameter space. (TC, Phalen, Pierce [arXiv:1001.3408])
- Does this generalize to generic WIMP's?

Why the Singlet-Doublet Model?

- We wish to study a simple model which captures all the relevant features of *strictly weakly interacting* dark matter.
- What about a vector-like doublet?
  - In this model, the effective operator $(\overline{D}\gamma^\mu D)(\overline{q}\gamma_\mu q)$ is generated via Z boson exchange.
  - This implies direct-detection cross sections which are far above current limits (up to dark matter masses of ~ 50 TeV).

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  - This implies direct-detection cross sections which are far above current limits (up to dark matter masses of ~ 50 TeV).
- If one splits this pure Dirac state into 2 Majorana states, this operator vanishes.
- One simple way to do this is by mixing the doublets with a singlet (analogous to Bino-Higgsino dark matter).
  - Note that the choice of a doublet allows renormalizable couplings to the Higgs boson.

Previous studies of singlet-doublet dark matter include: Arkani-Hamed, Dimopoulos, Kachru [arXiv:hep-ph/0512090]; Mahbubani, Senatore [arXiv:hep-ph/0510064]; D'Eramo [arXiv:0705.4493]; Enberg, Fox, Hall, Papaioanno, Papucci [arXiv:0706.0918].

Singlet-Doublet Fermion Model

Singlet-Doublet Fermion Model

- Add to the standard model, 3 Weyl fermions:
  - A singlet S
  - A pair of doublets

$$D = \begin{pmatrix} \nu \\ E \end{pmatrix} \qquad D^c = \begin{pmatrix} -E^c \\ \nu^c \end{pmatrix}$$

- The Lagrangian is given by (H is the Higgs boson)

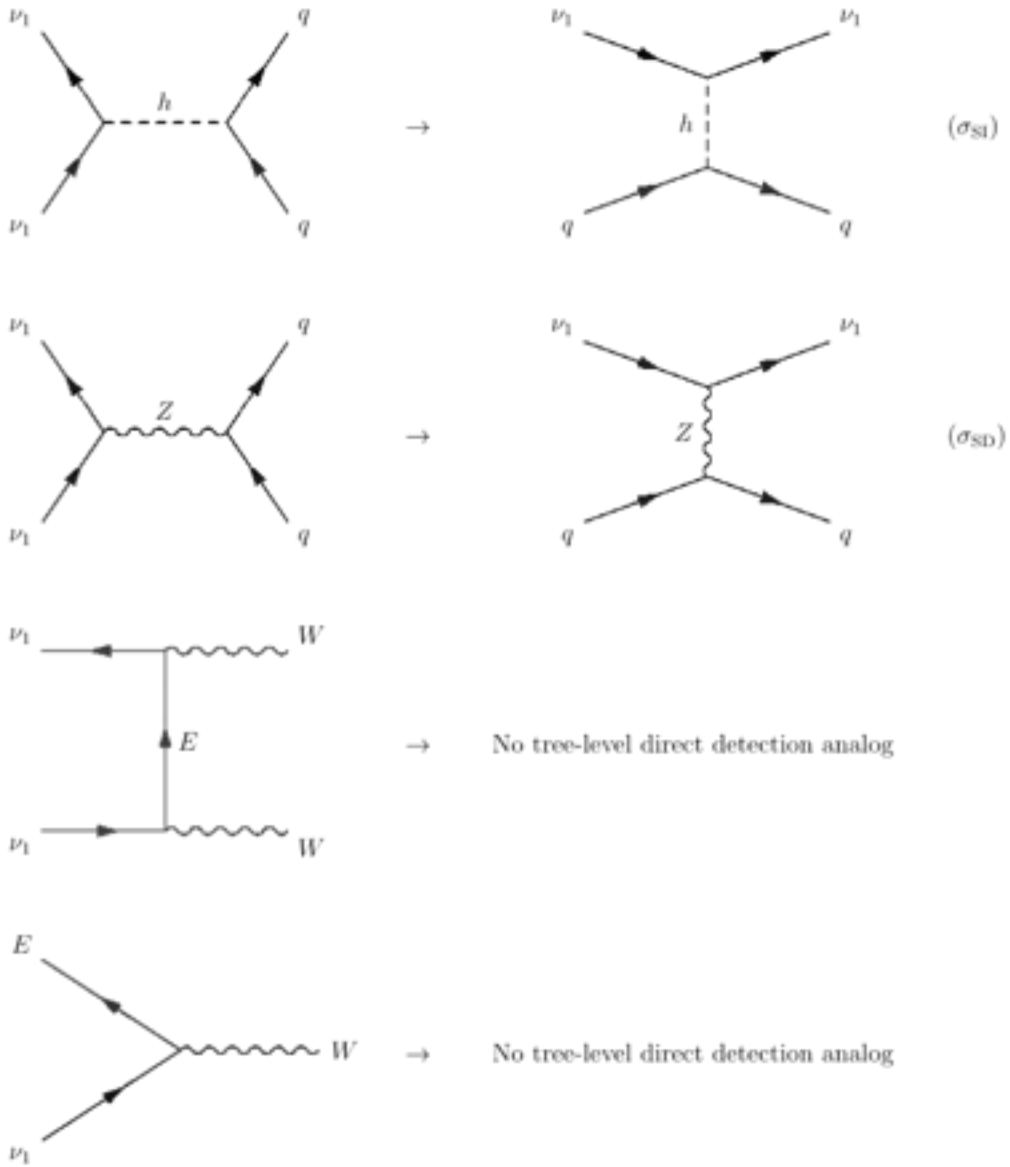
$$\Delta\mathcal{L} = -\lambda\, D\, H\, S - \lambda'\, D^c\, \tilde{H}\, S - M_D D\, D^c \; - \tfrac{1}{2} M_S S^2 + \text{ h.c.}$$

- This yields the following mass matrix in the basis $(S,\, \nu,\, \nu^c)$

$$\begin{pmatrix} M_S & \frac{\lambda}{\sqrt{2}}v & \frac{\lambda'}{\sqrt{2}}v \\ \frac{\lambda}{\sqrt{2}}v & 0 & M_D \\ \frac{\lambda'}{\sqrt{2}}v & M_D & 0 \end{pmatrix}$$

  - ν_1 is the dark matter.
  - The spectrum includes two additional neutral Majorana fermions and a charged fermion.

Annihilation and Direct Detection Diagrams



Aside on approximations

- We use MicrOMEGAs for all computations.
  - 3-body final states are not included.
  - This implies errors near the W^+W^- and $t\,\bar{t}$ thresholds.
- Direct detection only includes the leading tree level contributions.
  - Velocity suppressed contributions are neglected.
  - 1-loop diagrams become relevant for cross sections on the order of 10^{-9} pb . (Cirelli, Fornengo, Strumia [arXiv:hep-ph/0512090]; Essig [arXiv:0710.1668])
- New lattice results on the nuclear matrix elements can imply a reduction of a factor of 2.5 for the spin-independent cross section. (Giedt, Thomas, Young [arXiv:0904.4177])

Suppressing σ_{SI}

- The spin-independent cross section is due to interactions with the Higgs boson.
- How can one suppress this coupling?
- Take $M_D < M_S$.
  - For $\lambda = \lambda'$, the dark matter is pure doublet and the coupling to the Higgs boson vanishes.

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- Take $M_D < M_S$.
  - For $\lambda = \lambda'$, the dark matter is pure doublet and the coupling to the Higgs boson vanishes.
- Take $M_S < M_D$.
  - The mass of the dark matter can be written as

$$m_{\nu_1} = M_S + v\, f(M_S, M_D, \lambda\, v, \lambda' v).$$

  - By analyzing the characteristic equation for the mass matrix, one can solve for the condition that $m_{\nu_1} = M_S$:

$$\lambda'_{\rm crit} = -\lambda \frac{M_S}{M_D}\left(1 \pm \sqrt{1 - \left(\frac{M_S}{M_D}\right)^2}\right)^{-1}.$$

  - By gauge invariance, if $\lambda' = \lambda'_{\rm crit}$, the coupling to the Higgs boson also vanishes.

Suppressing σ_{SD}

- The coupling to the Z is proportional to $|Z_D|^2 - |Z_{\overline{D}}|^2$.
- This vanishes if the dark matter state contains equal parts D and $\overline{D}$.
- This occurs if either $\lambda = \lambda'$ or $\lambda = -\lambda'$.

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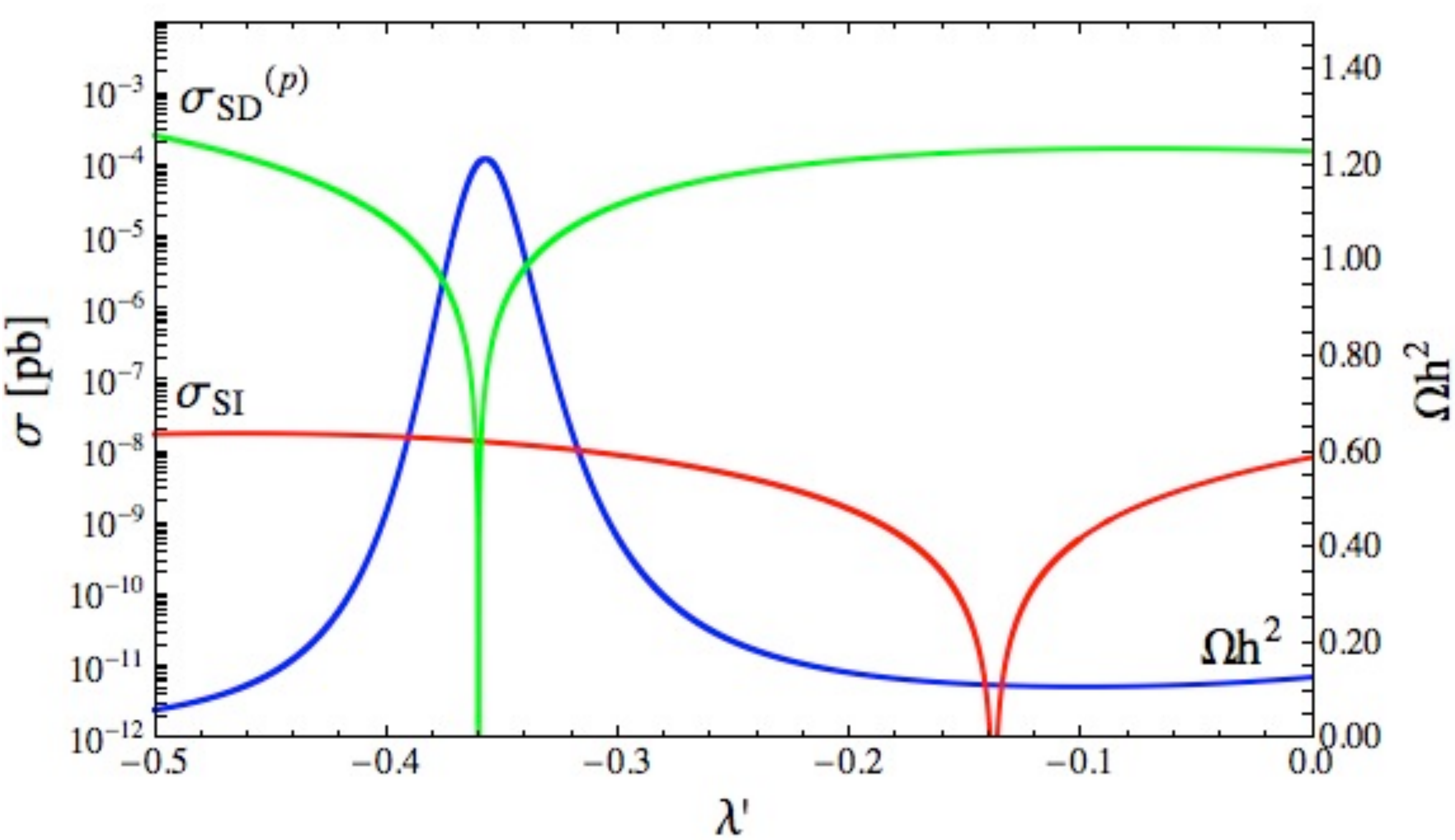
- This vanishes if the dark matter state contains equal parts D and $\overline{D}$.
- This occurs if either $\lambda = \lambda'$ or $\lambda = -\lambda'$.
- For $M_D < M_S$, this is the same condition for canceling the spin-independent cross section (the pure doublet limit).
    - If the dark matter is "doublet-like" one can suppress spin-independent and spin-dependent scattering off of nuclei.
- For $M_S < M_D$, it is not possible to satisfy this condition while imposing a vanishing coupling to the Higgs.
    - If the dark matter is "singlet-like" there should generically be either spin-independent, spin-dependent or both types of scattering off of nuclei.

An example of these cancelations



- The parameters are $M_S = 200$ GeV, $M_D = 300$ GeV, and $\lambda = 0.36$.

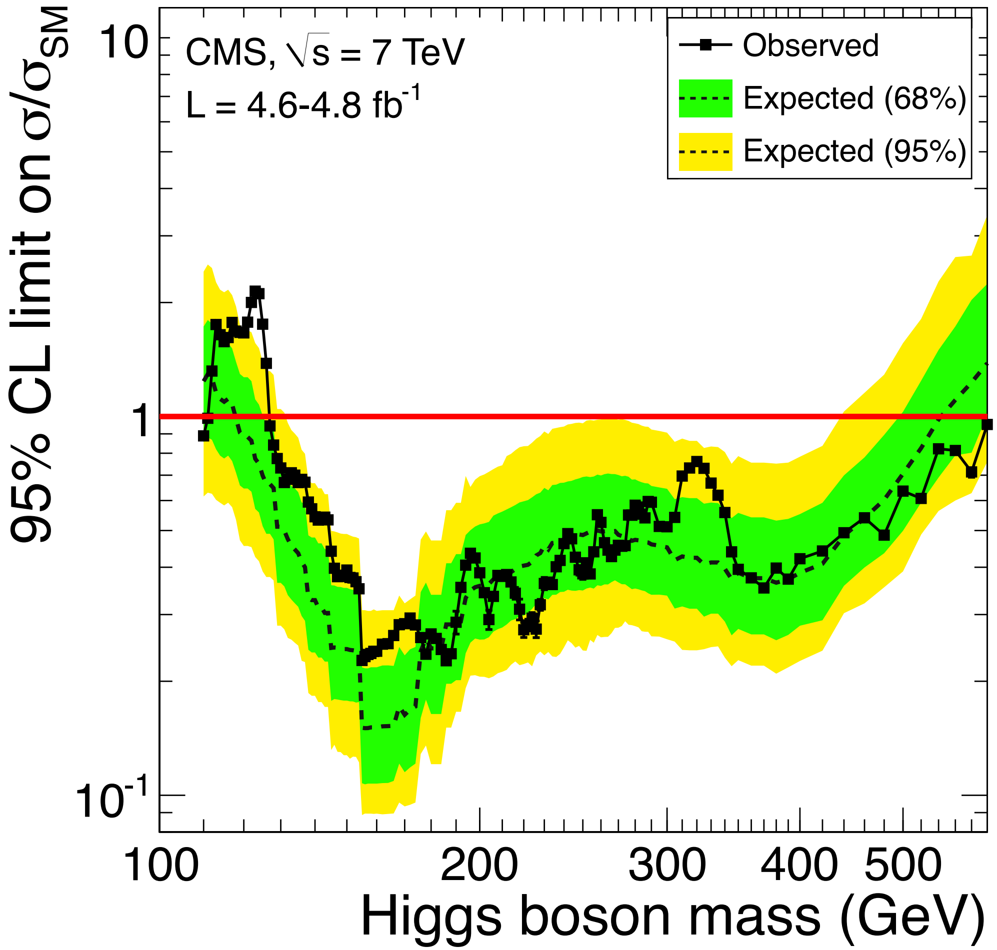
Pure doublet limit

- The dark matter has no coupling to the Higgs or the Z.
- It has full strength coupling to the $W^{\pm}$ and the E.
- Since the dark matter and the E are degenerate (up to radiative corrections), there will be co-annihilation.
- To achieve the correct relic density, $M_D \gtrsim 1.1 \text{ TeV}$.
- There will be no near-term observable direct detection in this scenario.
- (The purpose of the singlet in this case is to ensure that the dark matter is Majorana.)

Higgs mass bounds

(The CMS Collaboration [arXiv:1202.1488])

- CMS excludes from 127-600 GeV at 95% CL.



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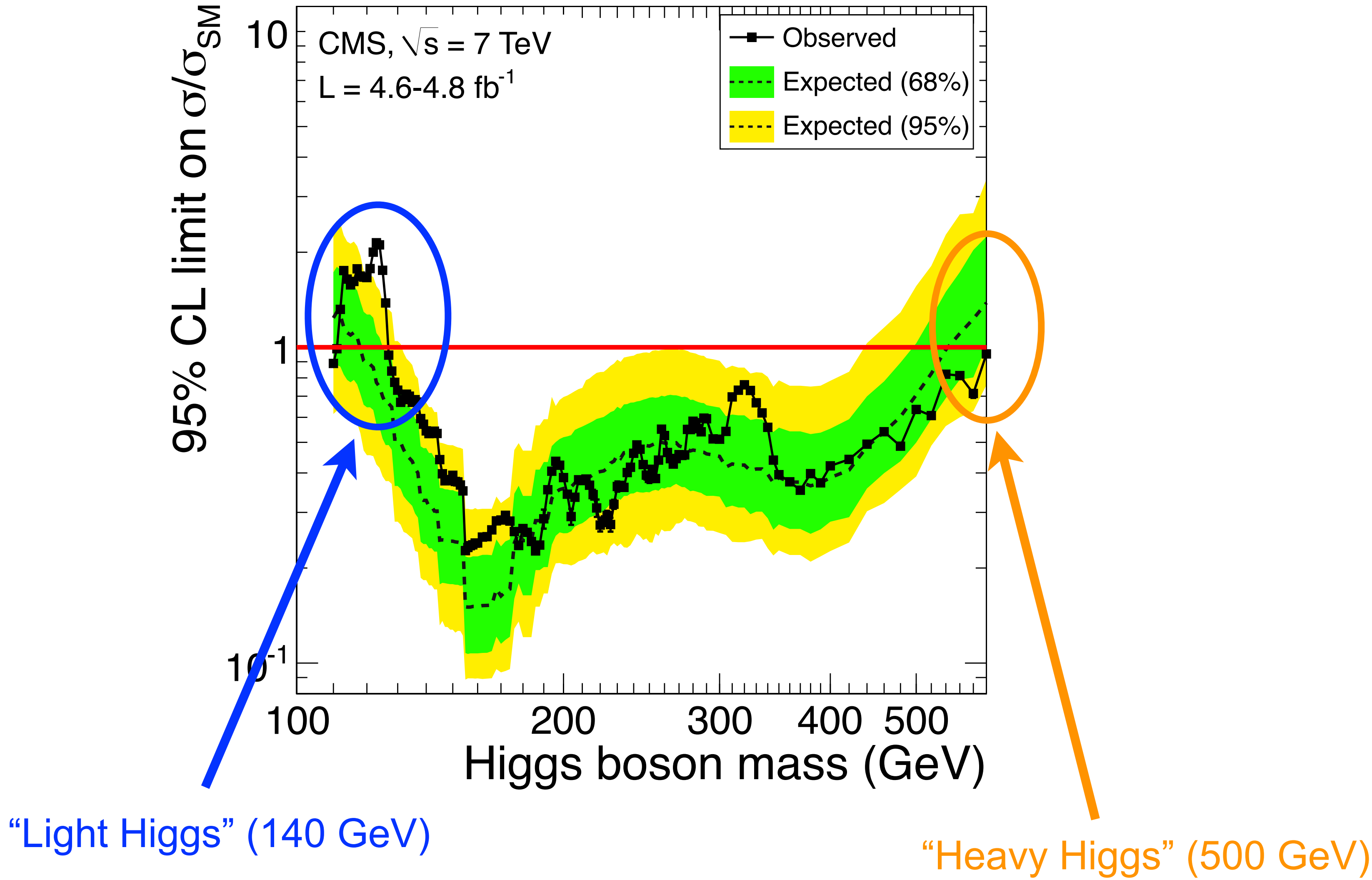

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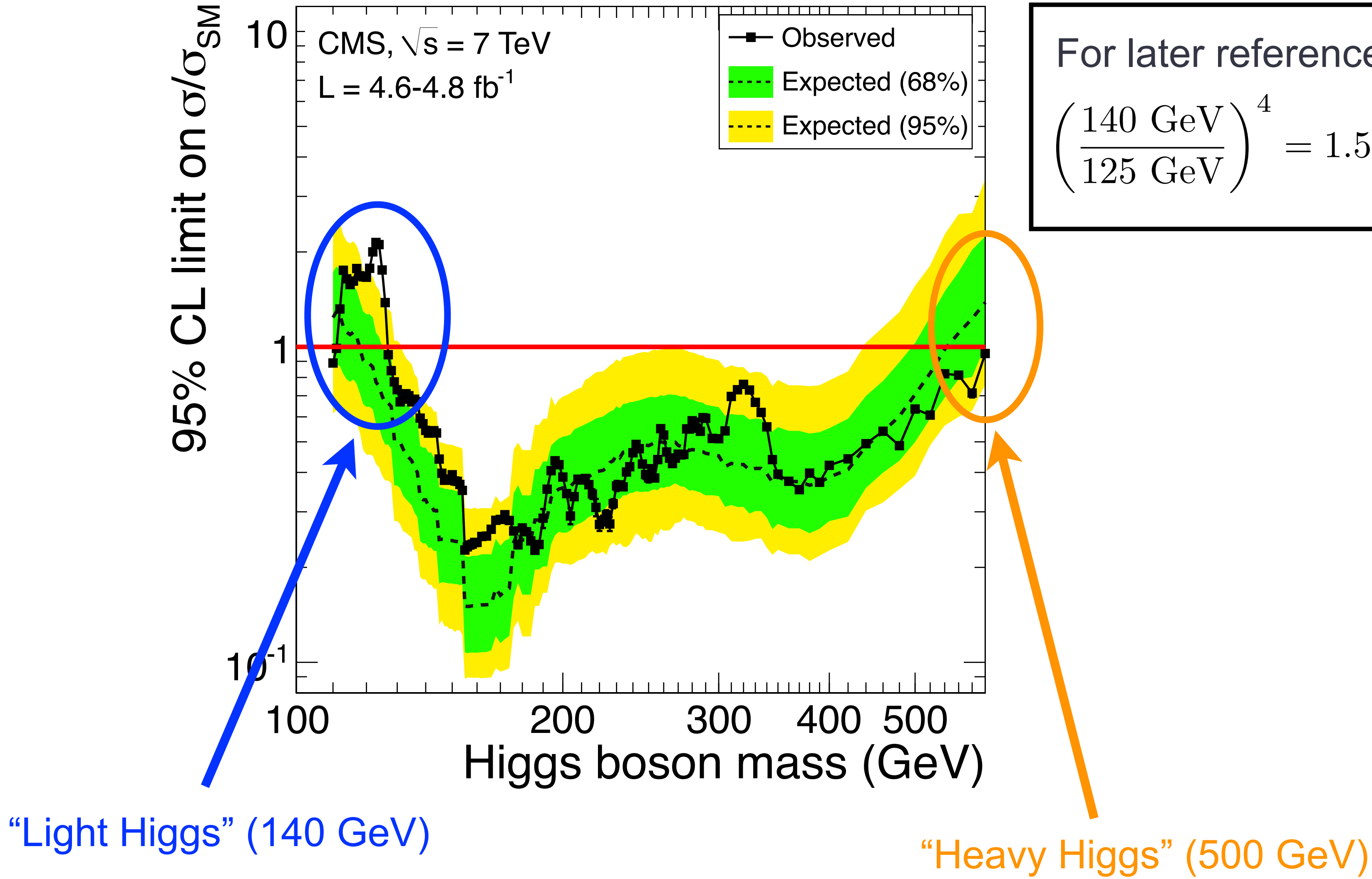

For later reference:

$$\left(\frac{140\ \text{GeV}}{125\ \text{GeV}}\right)^4 = 1.57$$

Projected limits

- Spin-independent
  - A one-ton Xe experiment can achieve on the order of 10^{-10} pb. (Xenon collaboration)
- Spin-dependent
  - COUPP is projected to reach $\sigma_{\rm SD} \sim 10^{-3} - 10^{-4}$ pb for dark matter masses between 10 - 500 GeV. (Benhnke et al. [arXiv:0804.2886])
  - The DeepCore extension of IceCube can place limits on the order of $\sigma_{\rm SD} \sim 2 \times 10^{-5} - 10^{-4}$ pb where the low end is for a dark matter mass of 100 GeV and the high end is for 500 GeV (assuming annihilation to $W^+ W^-$ in the sun) . (Wiebusch [arXiv:0907.2263])
  - Monojet bounds on contact operators from the LHC can also be relevant. (Rajaraman, Shepherd, Tait, Wijangco [arXiv:0810.0274])

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Projected spin-independent $O(10^{-10}$ pb)

Projected spin-dependent $O(10^{-(5-4)}$ pb)

Models with a Light Higgs

- As a benchmark, we take $m_h = 140\ \mathrm{GeV}$.
- Then in order to be consistent with precision electroweak measurements, we enforce that $-0.07 \leq \Delta T \leq 0.21$ from the dark sector. (D'Eramo [arXiv:0705.4493])
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- Contributions to S and U are negligible in these models.
- For the following results, we scanned the range

$$\begin{aligned} 0 \text{ GeV} \leq\ & M_S \leq 800 \text{ GeV} \\ 80 \text{ GeV} \leq\ & M_D \leq 2 \text{ TeV} \\ -2 \leq\ & \lambda \leq 2 \\ 0 \leq\ & \lambda' \leq 2 \end{aligned}$$

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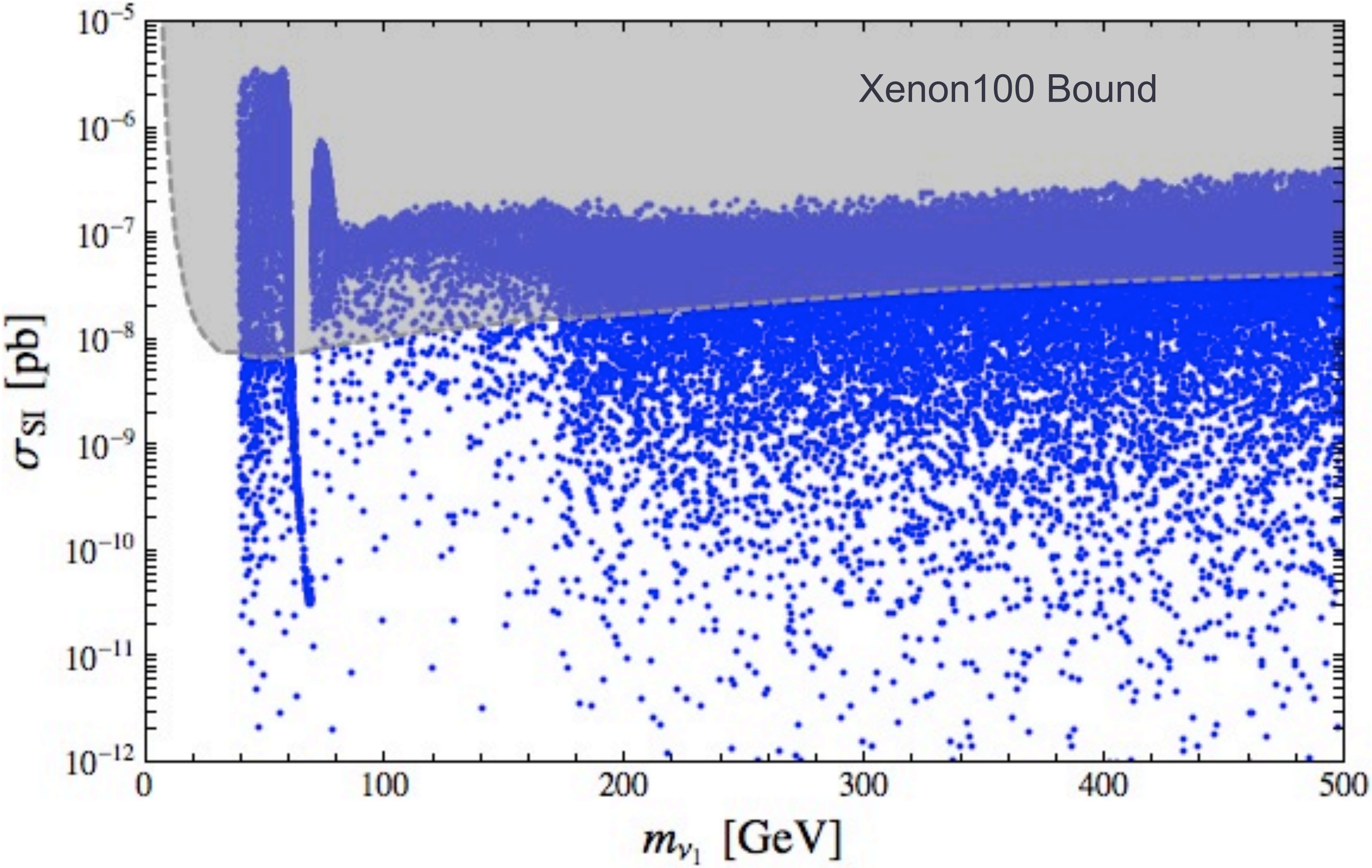
\begin{eqnarray*}
0\mbox{ GeV} \leq & \!
\!\!\! M_S &\!\!\!\!
\leq 800 \mbox{ GeV}\\
80\mbox{ GeV} \leq &
\!\!\!\! M_D & \!\!\!
\! \leq 2 \mbox{ TeV}\
\
-2 \leq & \!\!\!\!
```

- with the requirement that

$$40 \text{ GeV} \leq m_{\text{DM}} \leq 500 \text{ GeV}; \qquad 0.1053 \leq \Omega h^2 \leq 0.1193$$

$\sigma_{\rm SI}$ versus $m_{\rm DM}$ ($m_h = 140$ GeV)



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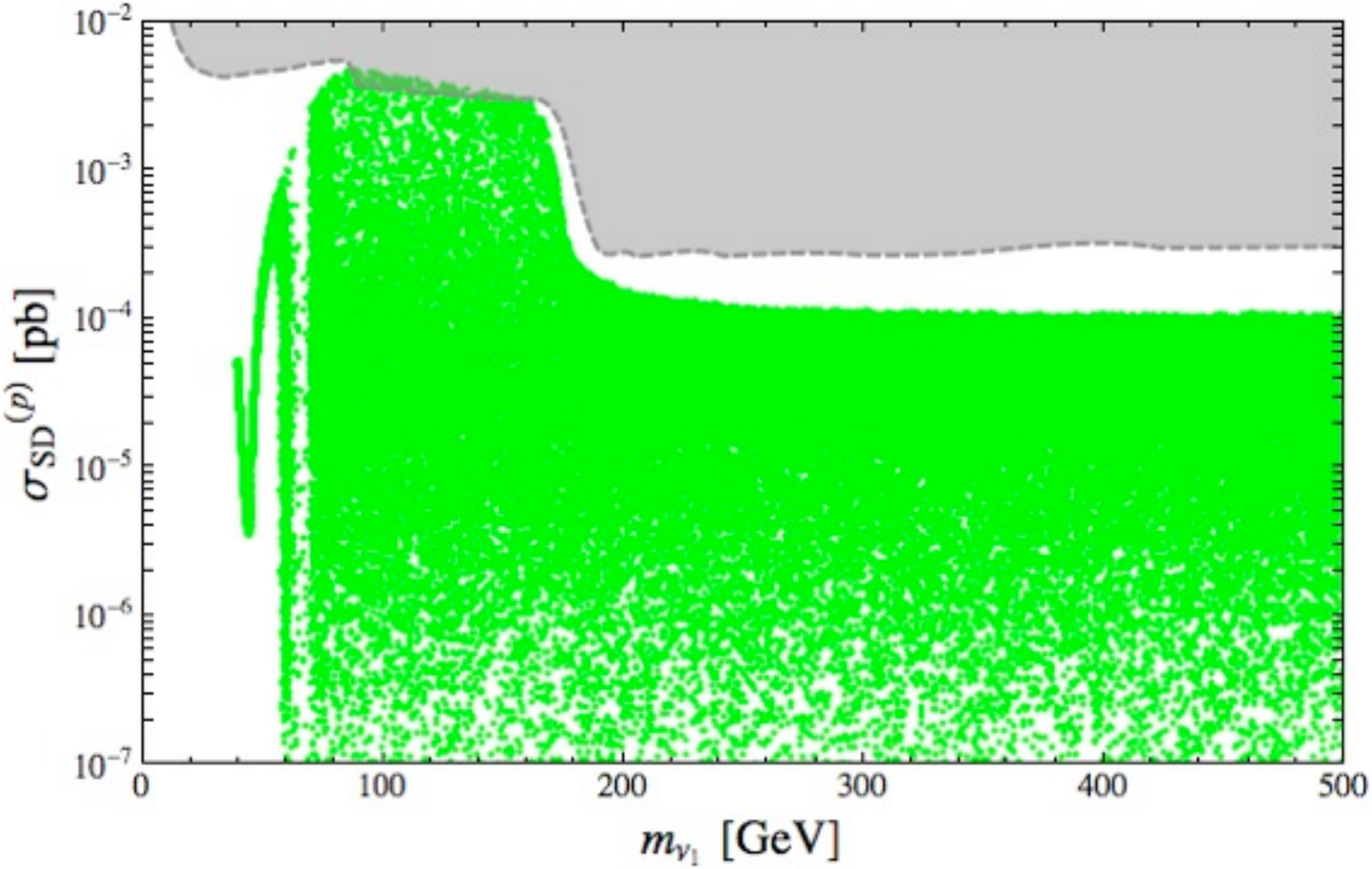

(For a detailed discussion of the Super-K bounds see Kearney, Pierce [arXiv:1202.0284])

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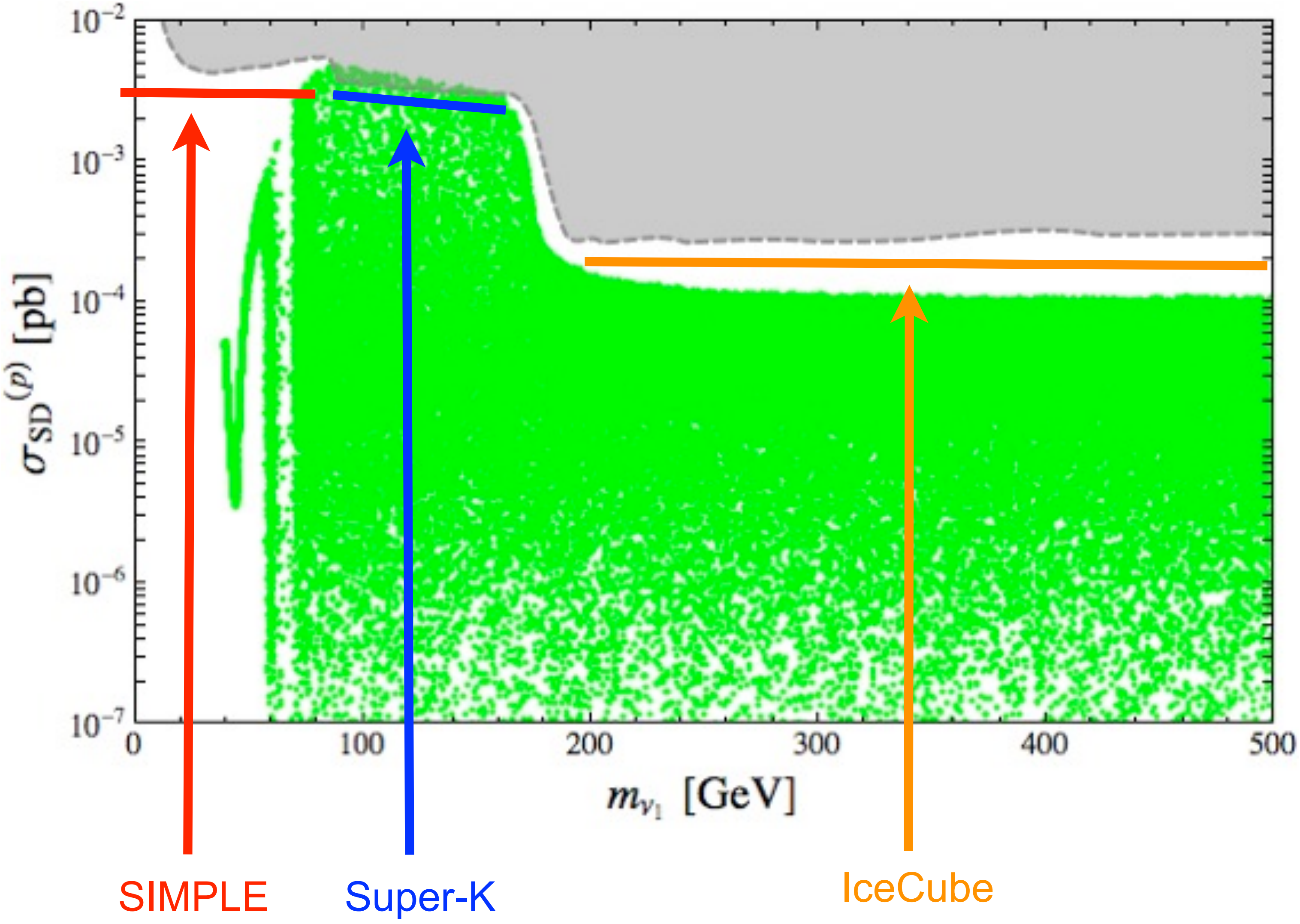

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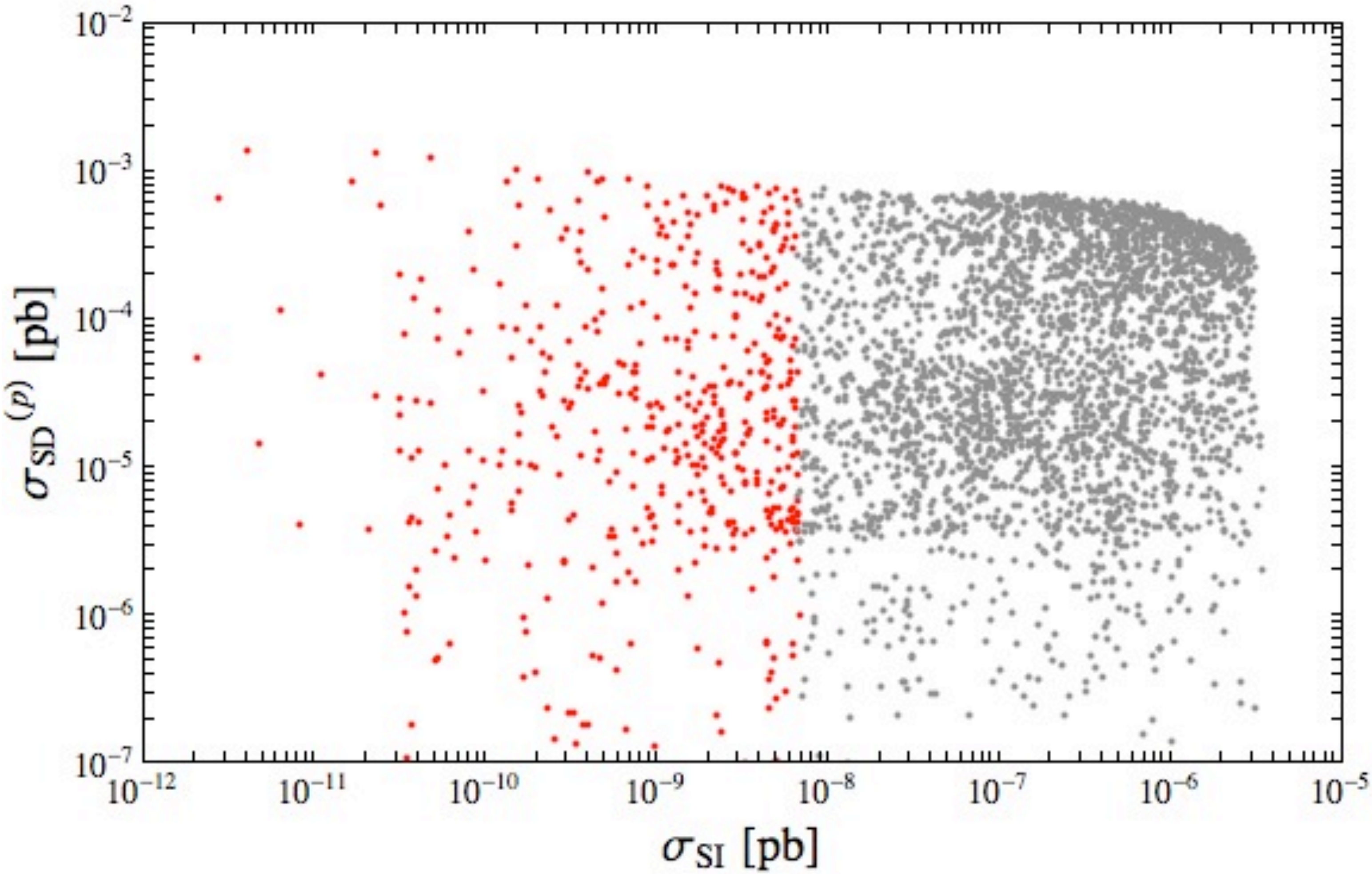
$\sigma_{\rm SD}$ versus $\sigma_{\rm SI}$ for light dark matter



- $m_{\nu_1} \leq 70$ GeV
- Grey is already excluded.

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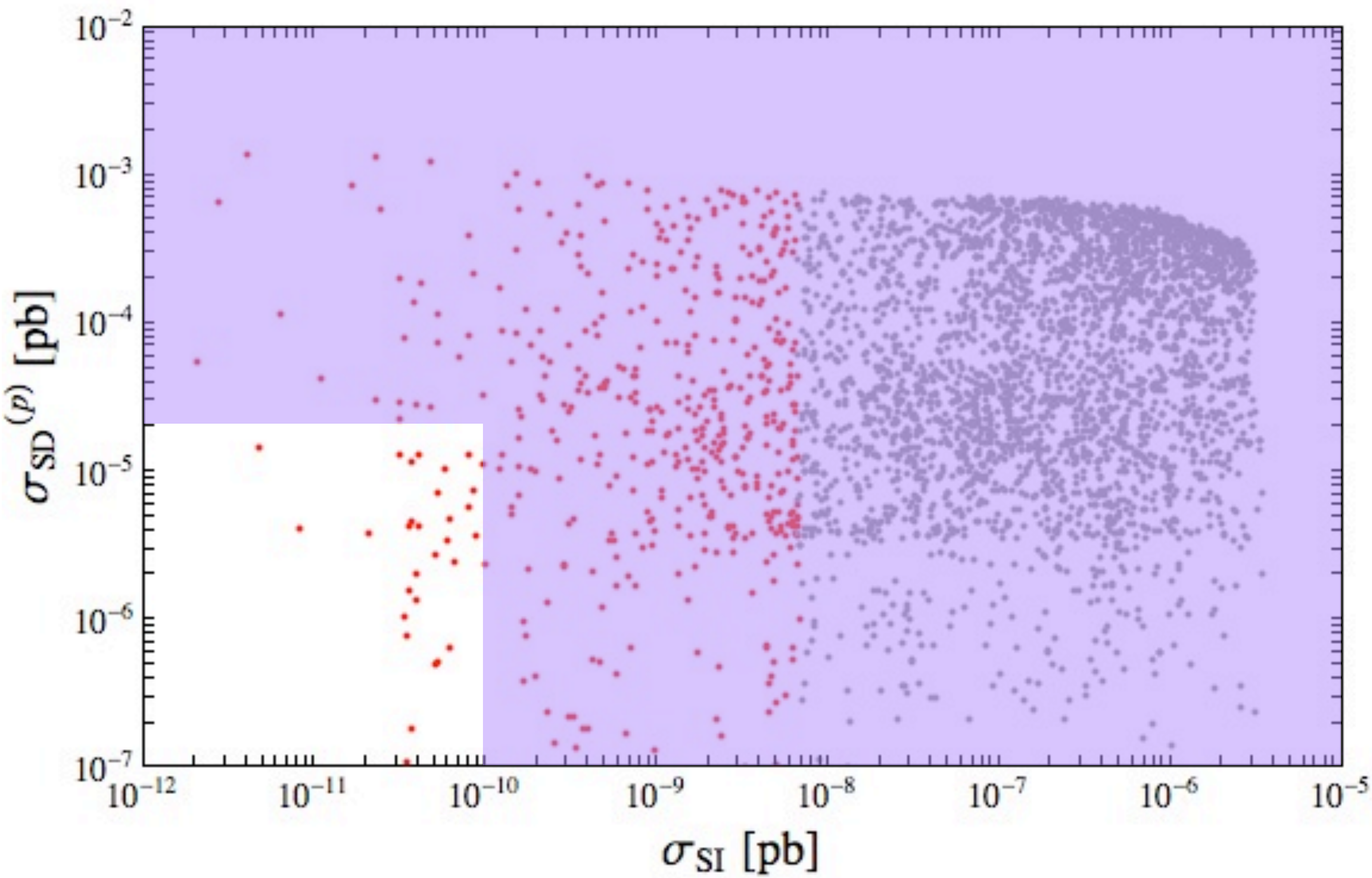

- $m_{\nu_1} \leq 70$ GeV
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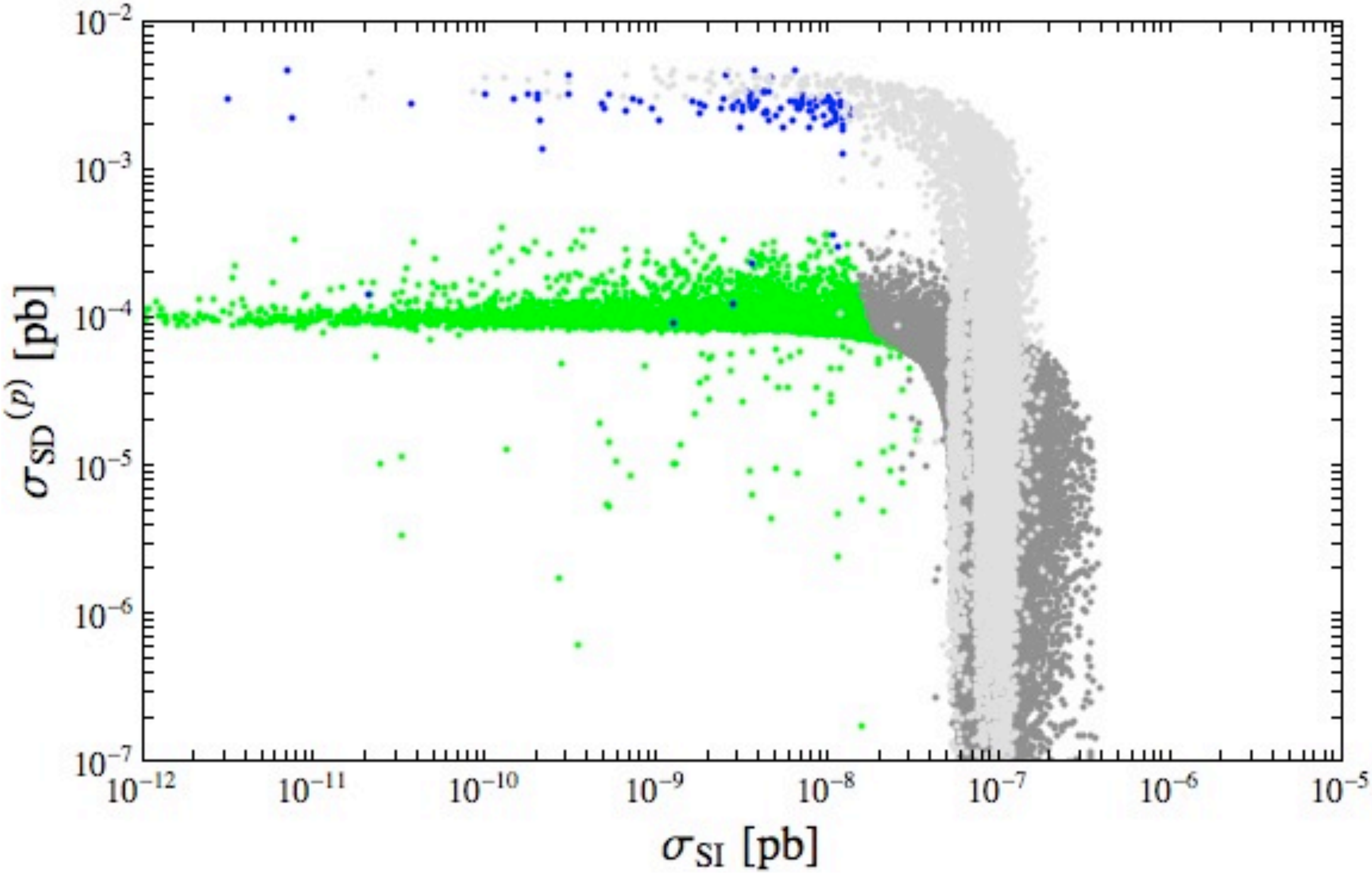
$\sigma_{\rm SD}$ versus $\sigma_{\rm SI}$ for heavy dark matter



- Blue (and light grey): $85\ \mathrm{GeV} \leq m_{\nu_1} \leq 160\ \mathrm{GeV}$
- Green (and dark grey): $175\ \mathrm{GeV} \leq m_{\nu_1} \leq 500\ \mathrm{GeV}$
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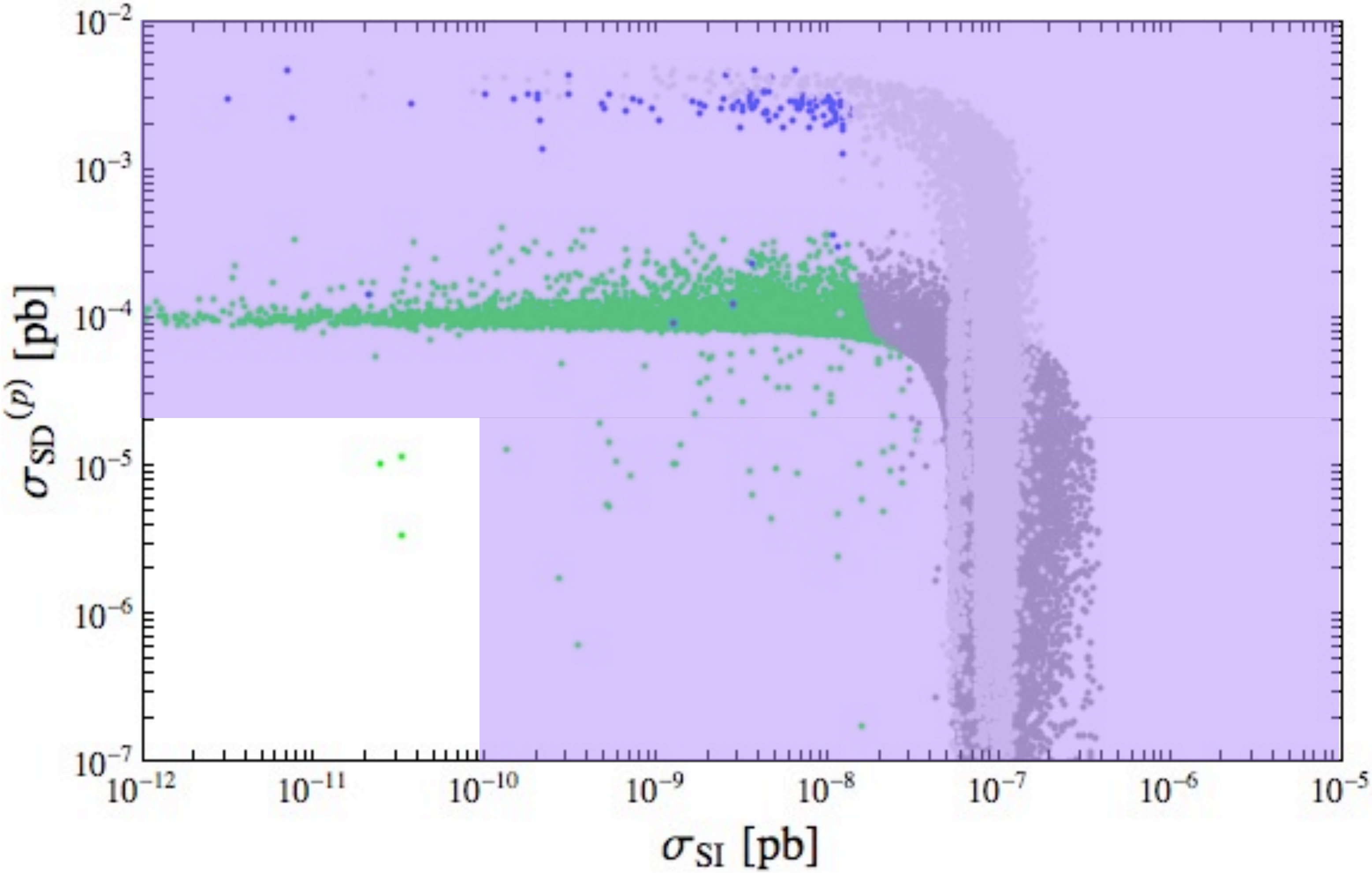

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Summary: Options for Avoiding Exclusion

i) $m_{\nu_1} \simeq \frac{m_Z}{2}$ or $m_{\nu_1} \simeq \frac{m_h}{2}$: the relic density can be achieved with suppressed couplings due to the resonant enhancement of the annihilation cross section.

ii) $m_{\nu_1} \simeq m_{\nu_2}$ or $m_{\nu_1} \simeq m_E$: t-channel processes or co-annihilation is important.

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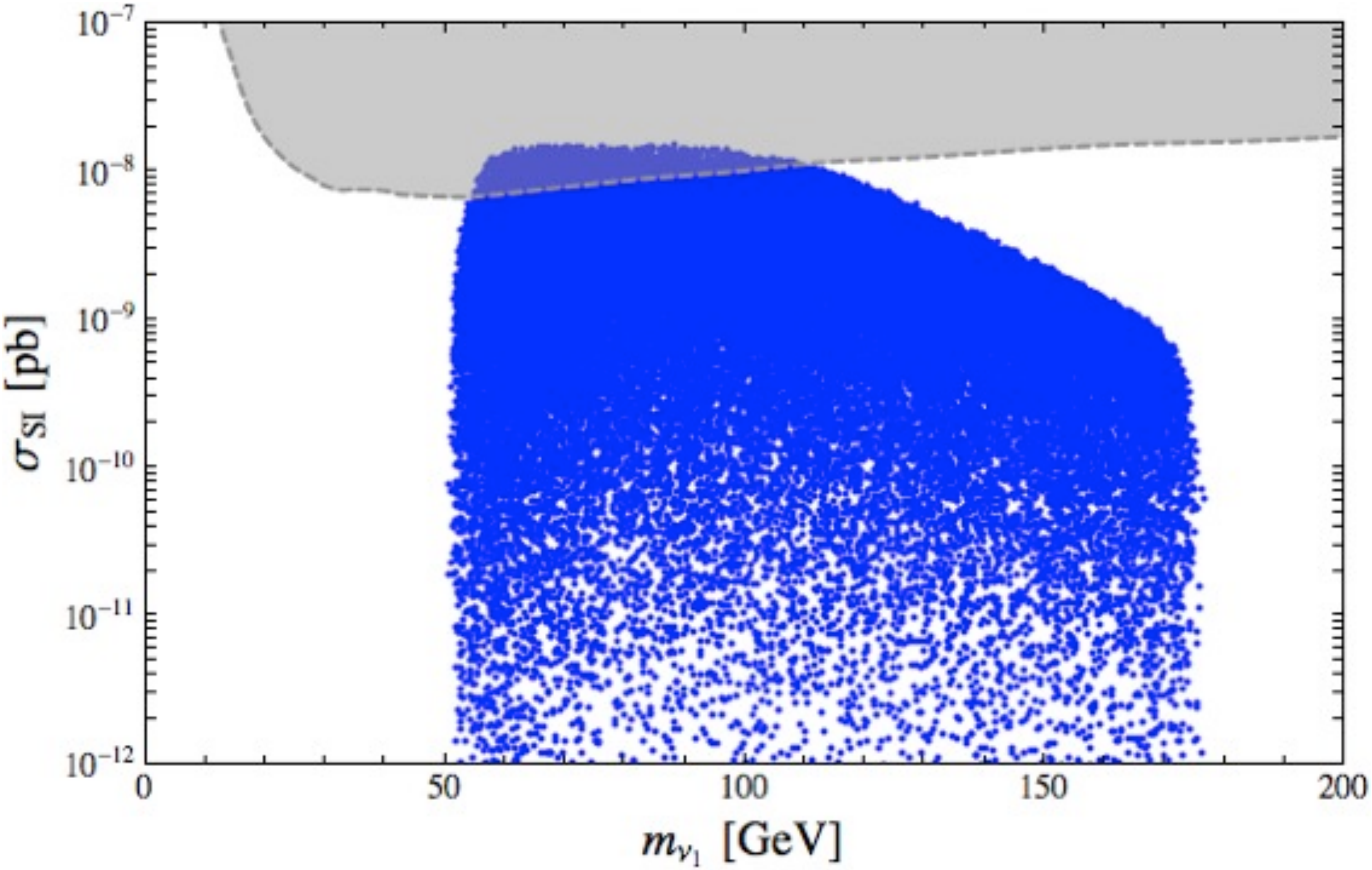
- We see that with future data, we will probe a large range of the parameter space of the singlet-doublet model (with a light Higgs boson).
  - The exception is for exceptional points (resonant annihilation, co-annihilation, etc.) where one must tune the parameters of the model.

Models with a Heavy Higgs

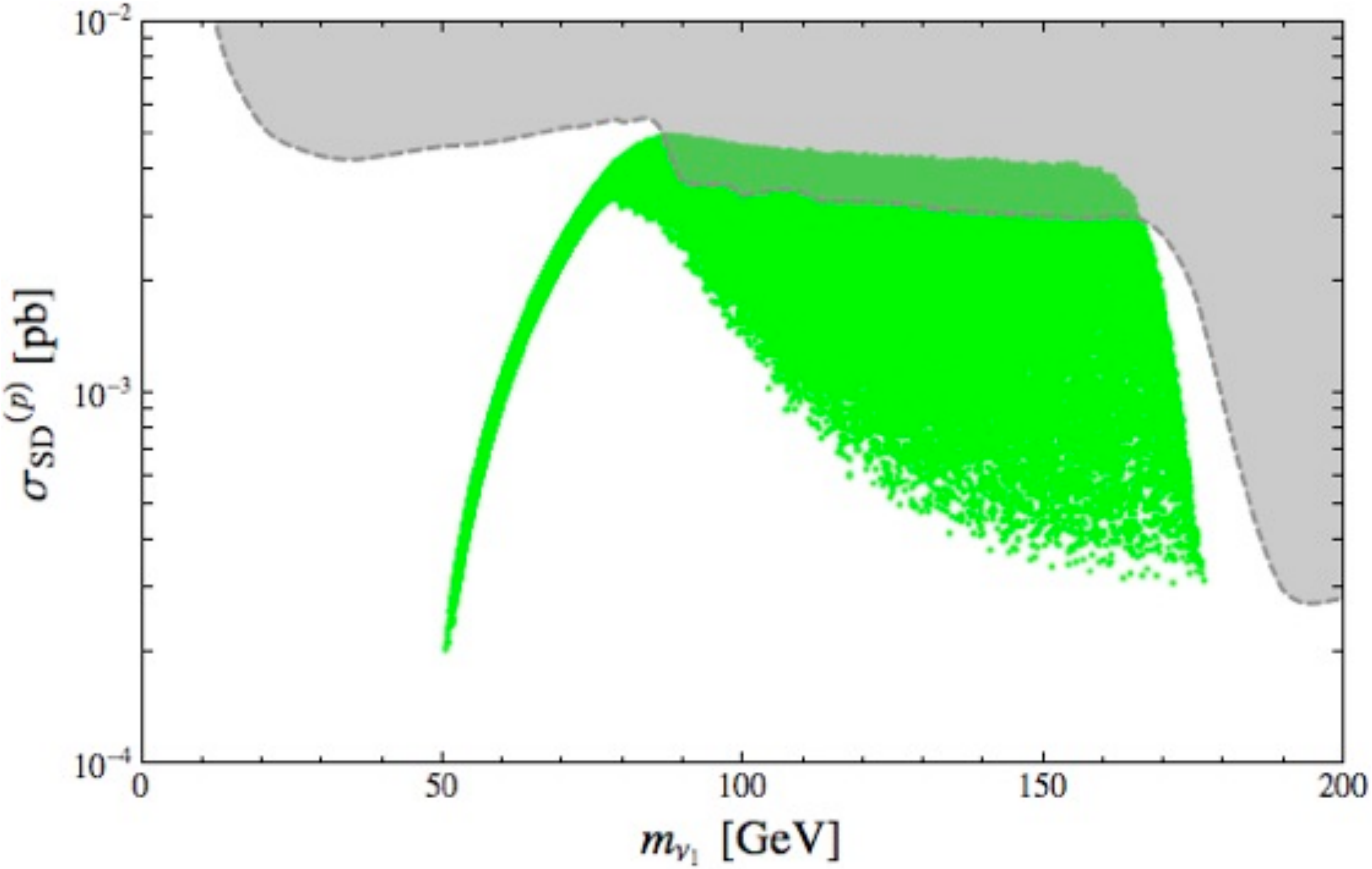
- As a benchmark we take $m_h = 500\ \mathrm{GeV}$.
- In order to compensate for the contribution from a heavy Higgs to precision electroweak, we enforce that $0.16 \leq \Delta T \leq 0.4$ from the dark sector.
- This implies that either λ or λ' will be non-zero and that they must be different.
- Hence, in this model there will always be a non-trivial coupling to the Z boson.
- If one does not require the contribution to ΔT from the dark sector, the spin-independent cross section can be suppressed by making the Higgs heavy.

$\sigma_{\rm SI}$ versus $m_{\rm DM}$ ($m_h = 500$ GeV)



- No points with $m_{\nu_1} \lesssim 50$ GeV and $m_{\nu_1} \gtrsim m_{\rm top}$ due to the ΔT requirement.

$\sigma_{\rm SD}$ versus $m_{\rm DM}$ ($m_h = 500\ {\rm GeV}$)



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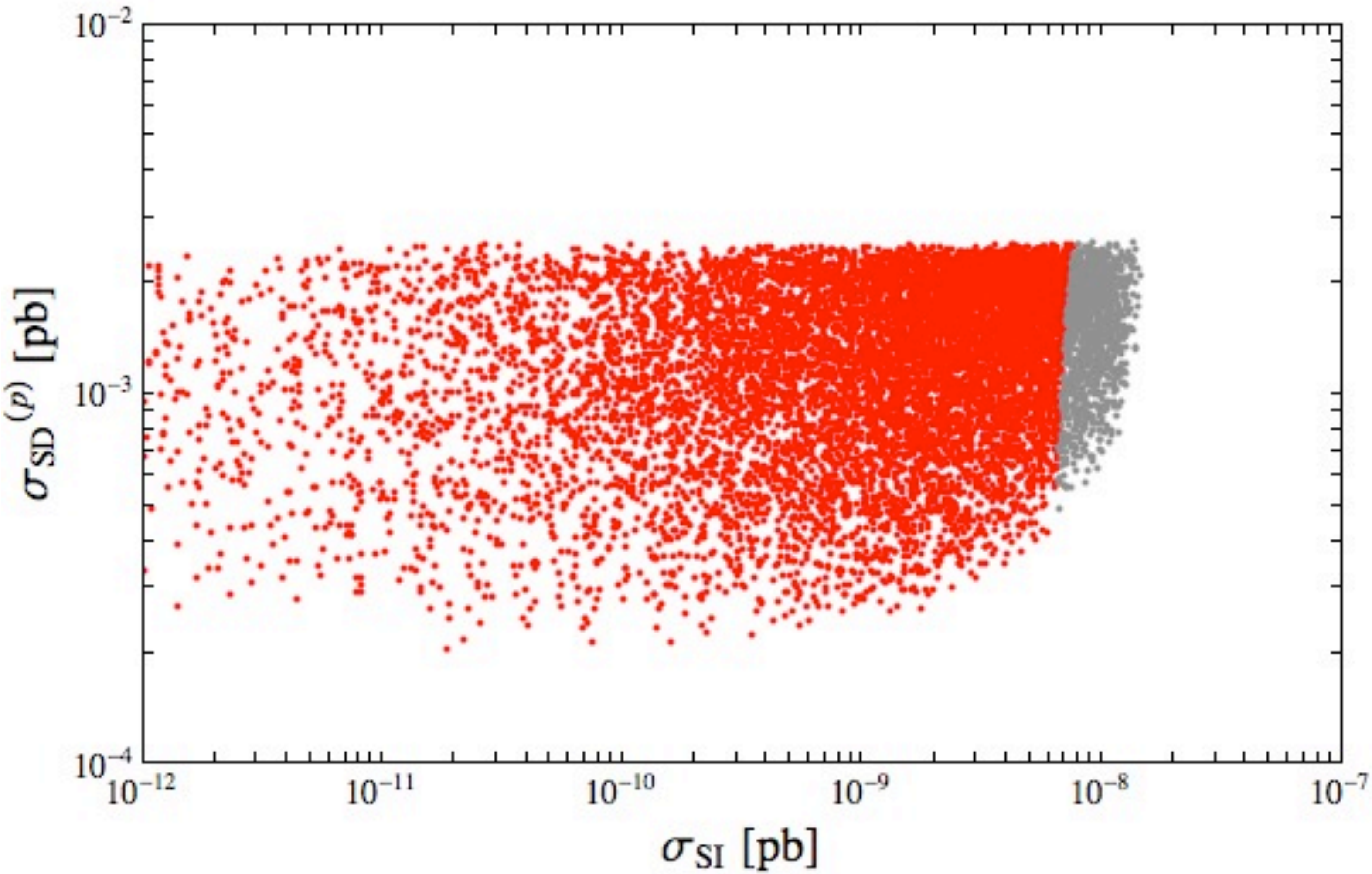
$\sigma_{\rm SD}$ versus $\sigma_{\rm SI}$ for light dark matter



- Restricted to $m_{\nu_1} \leq 70$ GeV.
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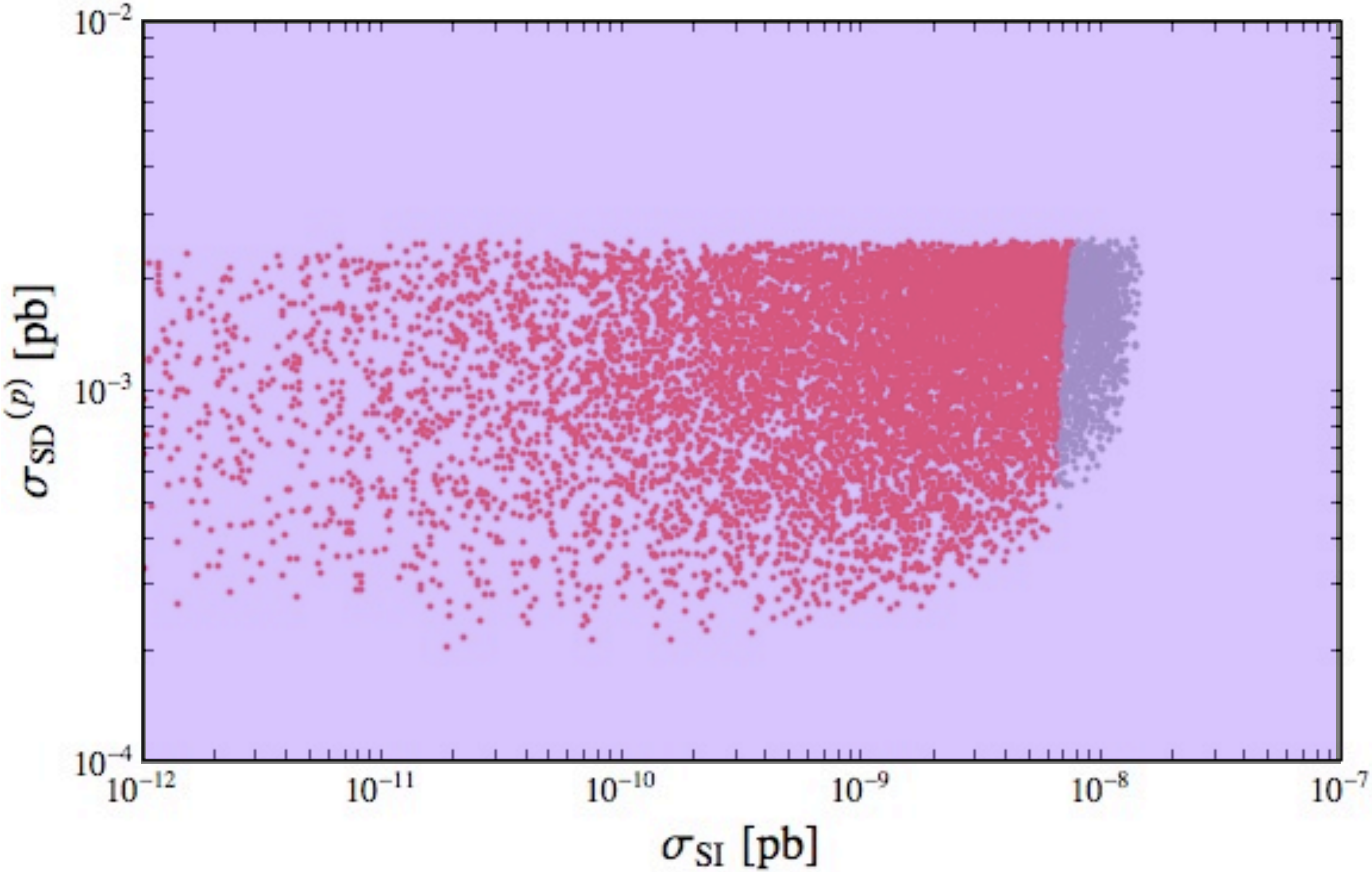

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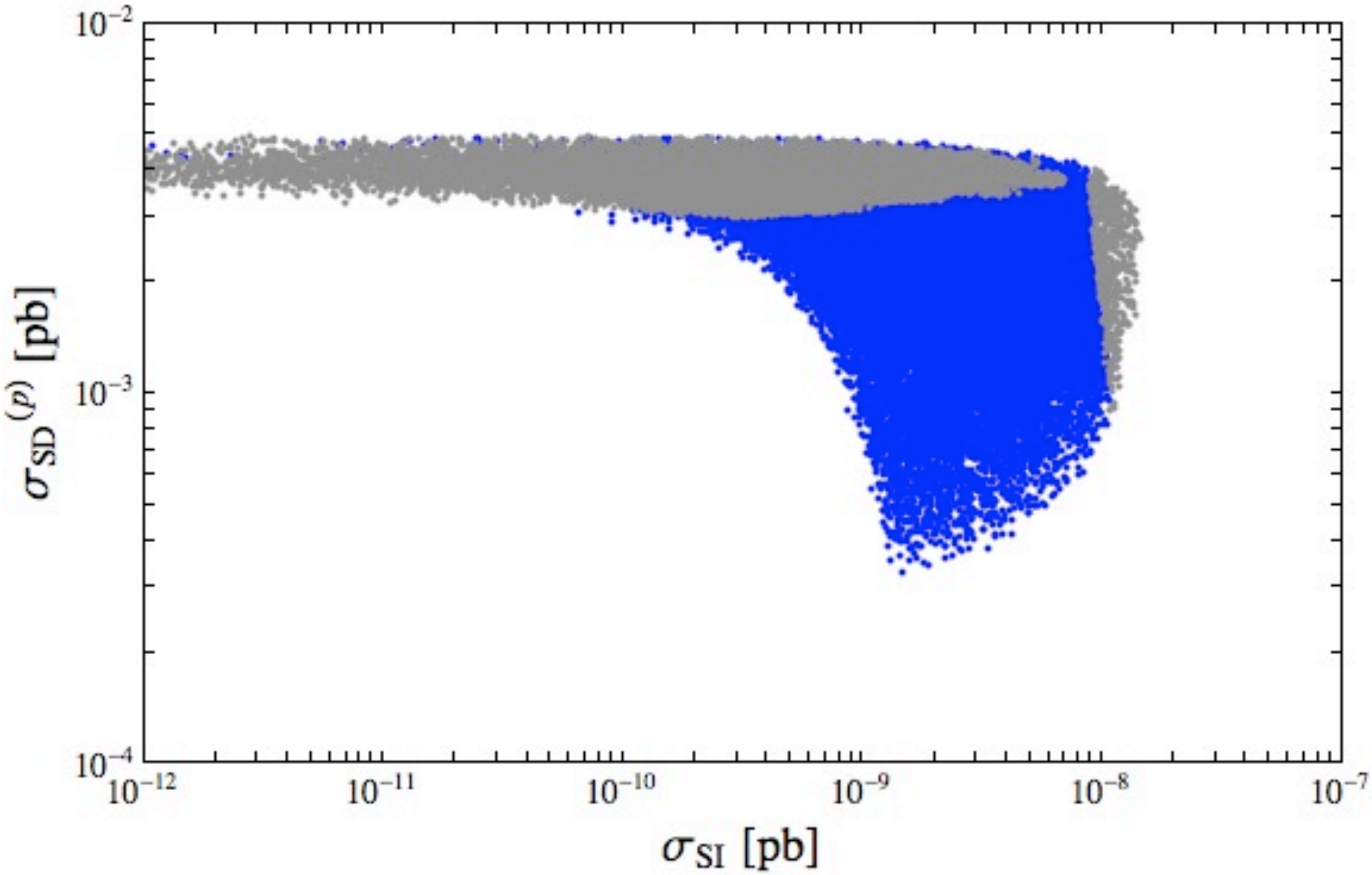

- Restricted to $m_{\nu_1} \geq 85$ GeV.
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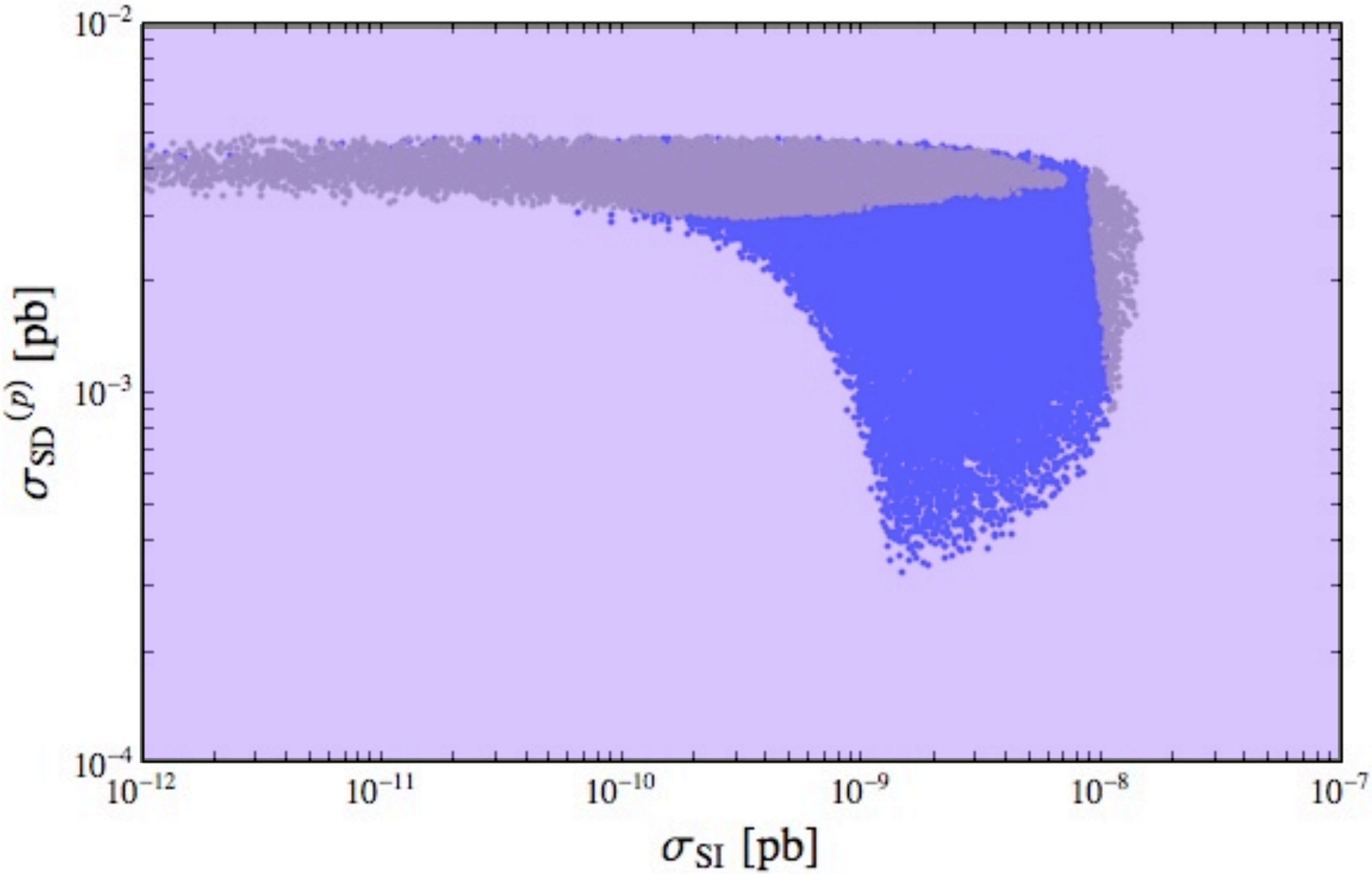
$\sigma_{\rm SD}$ versus $\sigma_{\rm SI}$ for heavy dark matter



- Restricted to $m_{\nu_1} \geq 85$ GeV.
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Singlet-Doublet Scalar Model

Singlet-Doublet Scalar Model

(The model without the doublet was recently studied by Farina, Pappadopulo, Strumia [arXiv:0912.5038])

- Add to the standard model
  - a singlet read scalar S,
  - a complex doublet (with hypercharge 1/2), $\Phi \equiv \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}\left(\phi^0 + iA^0\right) \end{pmatrix}$
- The Lagrangian is given by

$$\Delta\mathcal{L} = -m_D^2 \Phi^\dagger \Phi - \frac{m_S^2}{2} S^2 - g(S\,\Phi^\dagger\, H + \text{h.c.}) - \frac{\lambda_S}{2} S^2 H^\dagger H$$

- The dark matter is the lightest neutral scalar:

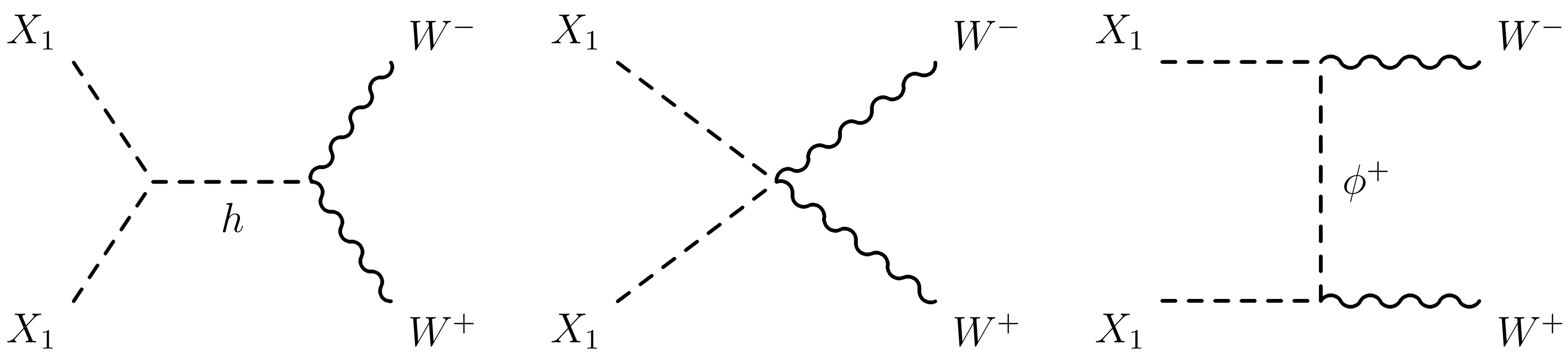
$$X_1 = \cos\,\theta\, S + \sin\,\theta\,\phi^0$$

- We will be interested in the effective coupling between the dark matter and the Higgs boson:

$$-(\lambda_S v \cos^2\theta - 2g\sin\theta\cos\theta)X_1^2 h \equiv -A_{\text{eff}} X_1^2 h$$

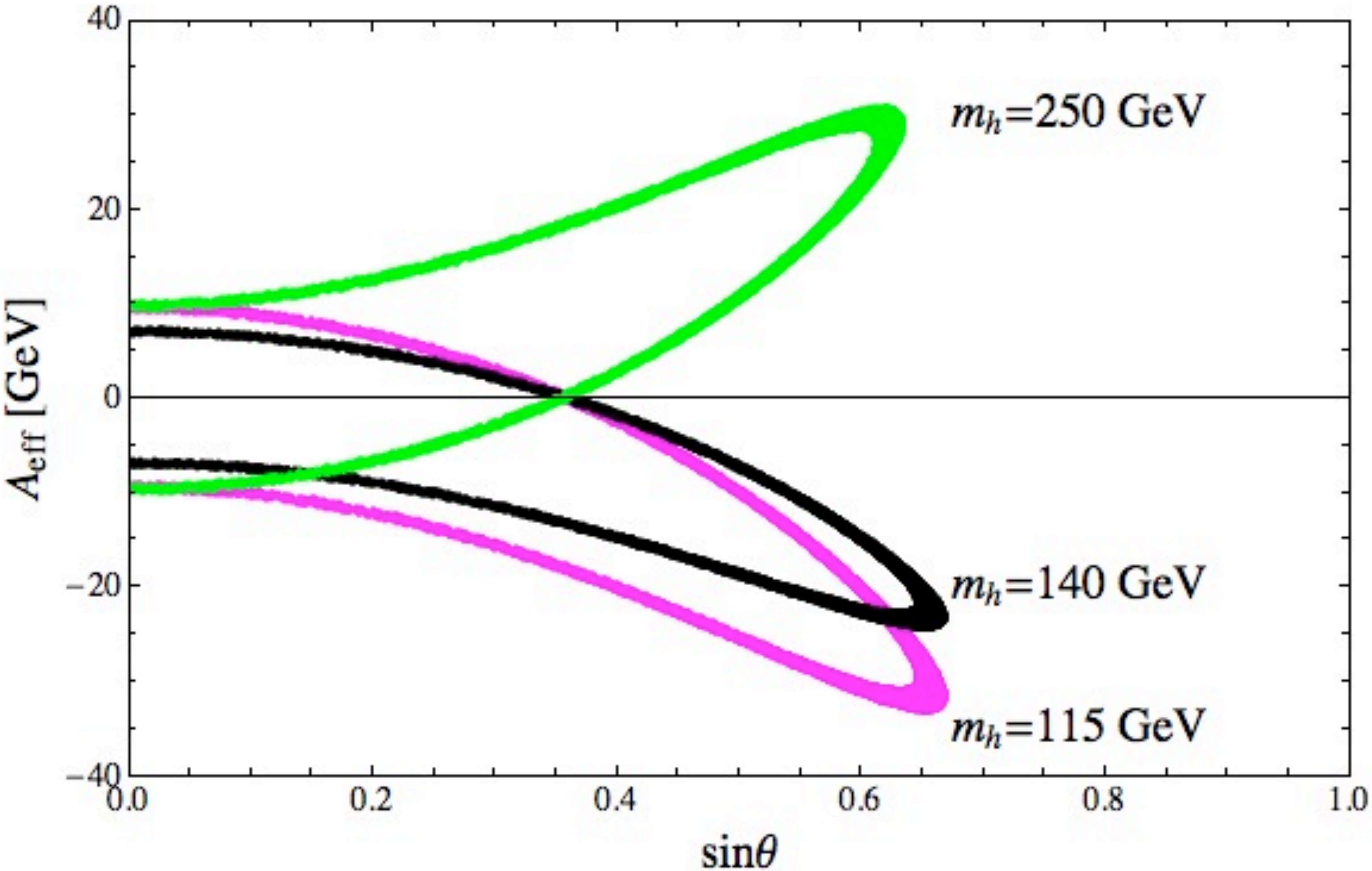
  - For simplicity we have set the following couplings to zero:
    $$-\lambda_1 (H^\dagger H)(\Phi^\dagger\Phi) - \lambda_2\left((\Phi^\dagger H)^2 + \text{h.c.}\right) - \lambda_3 (\Phi^\dagger H)(H^\dagger \Phi)$$
  - This ensures that there will be no co-annihilation.

Annihilation Diagrams



- Note the possibility of interference.

Dependence on $\sin\theta$



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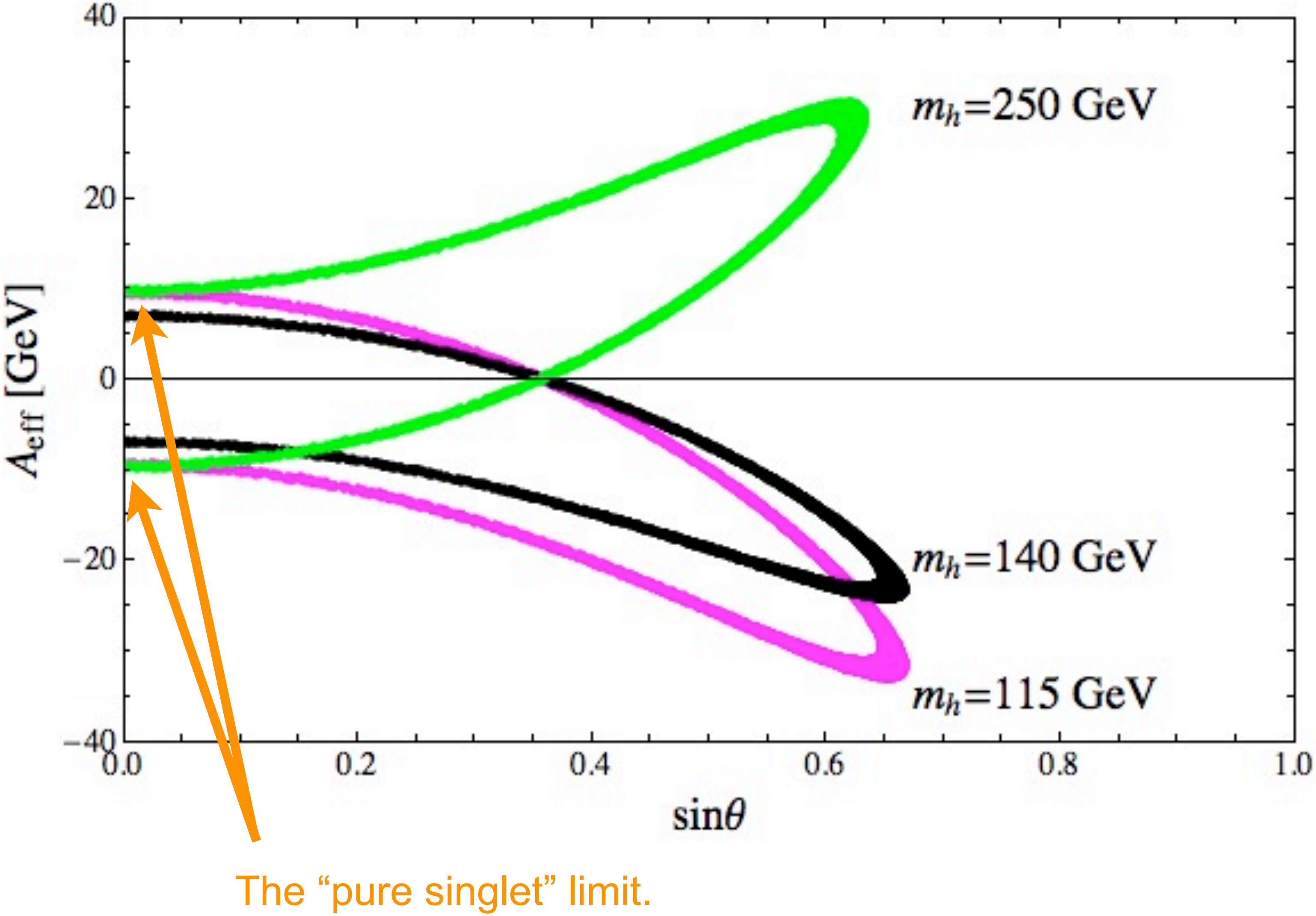

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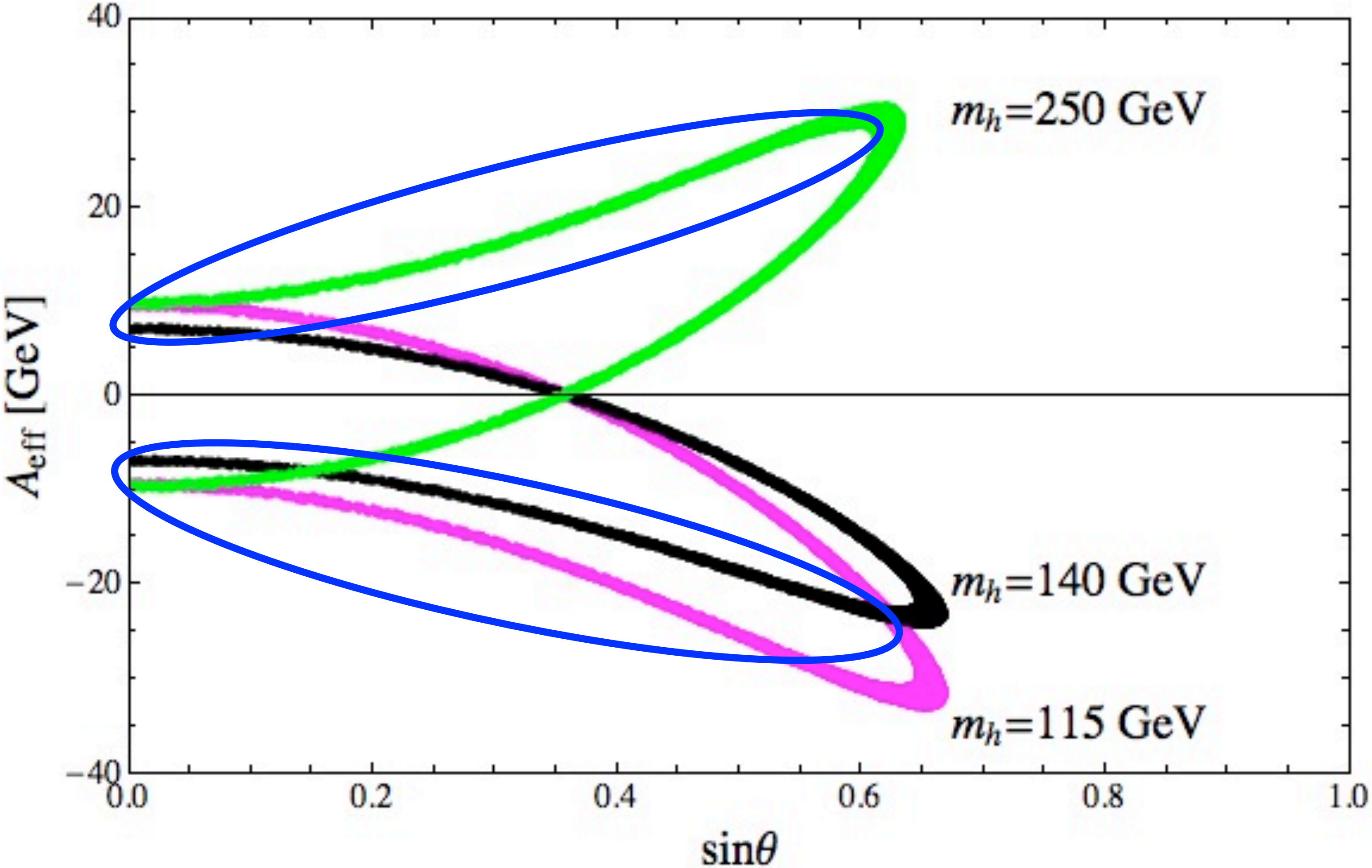
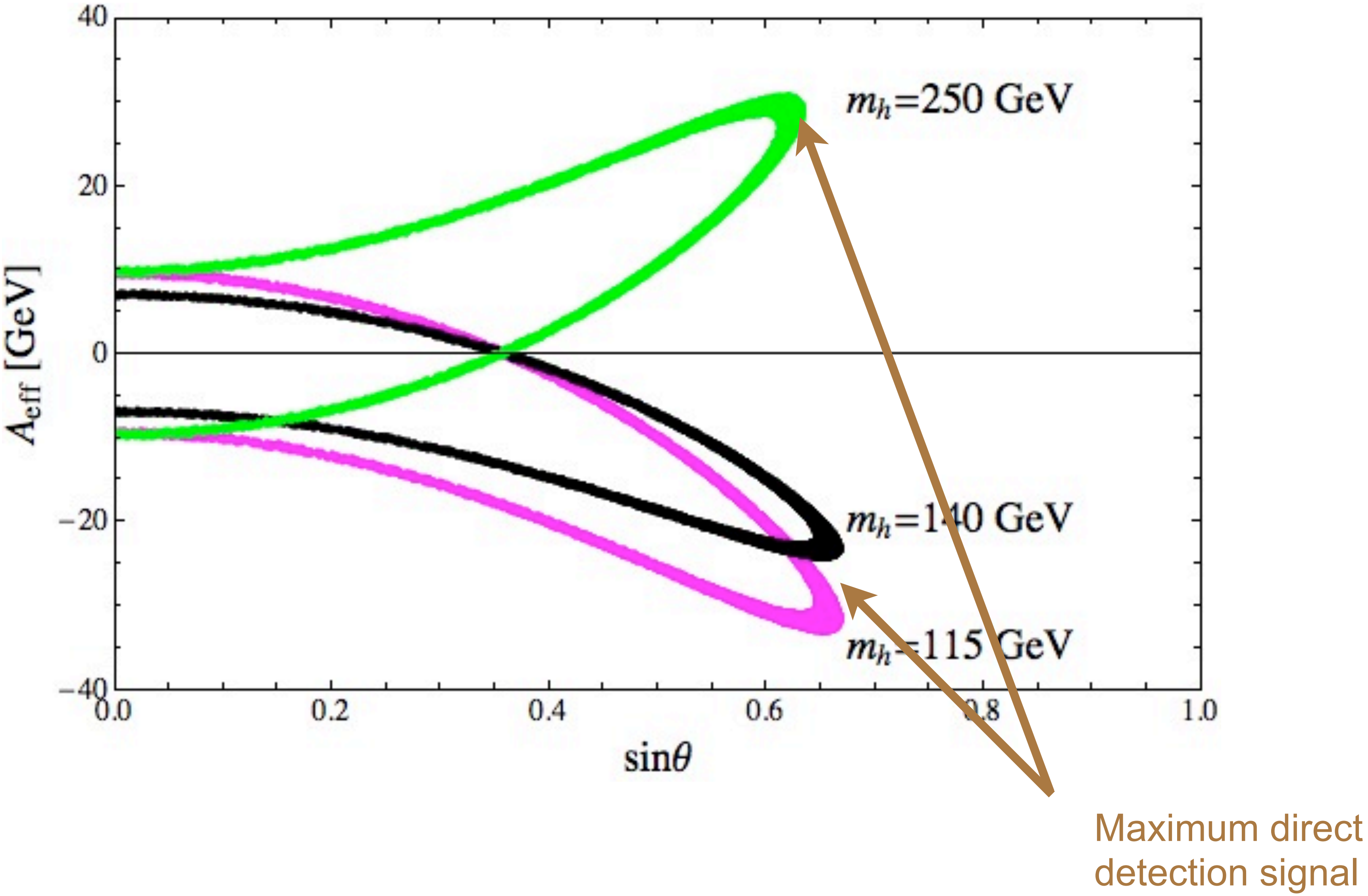
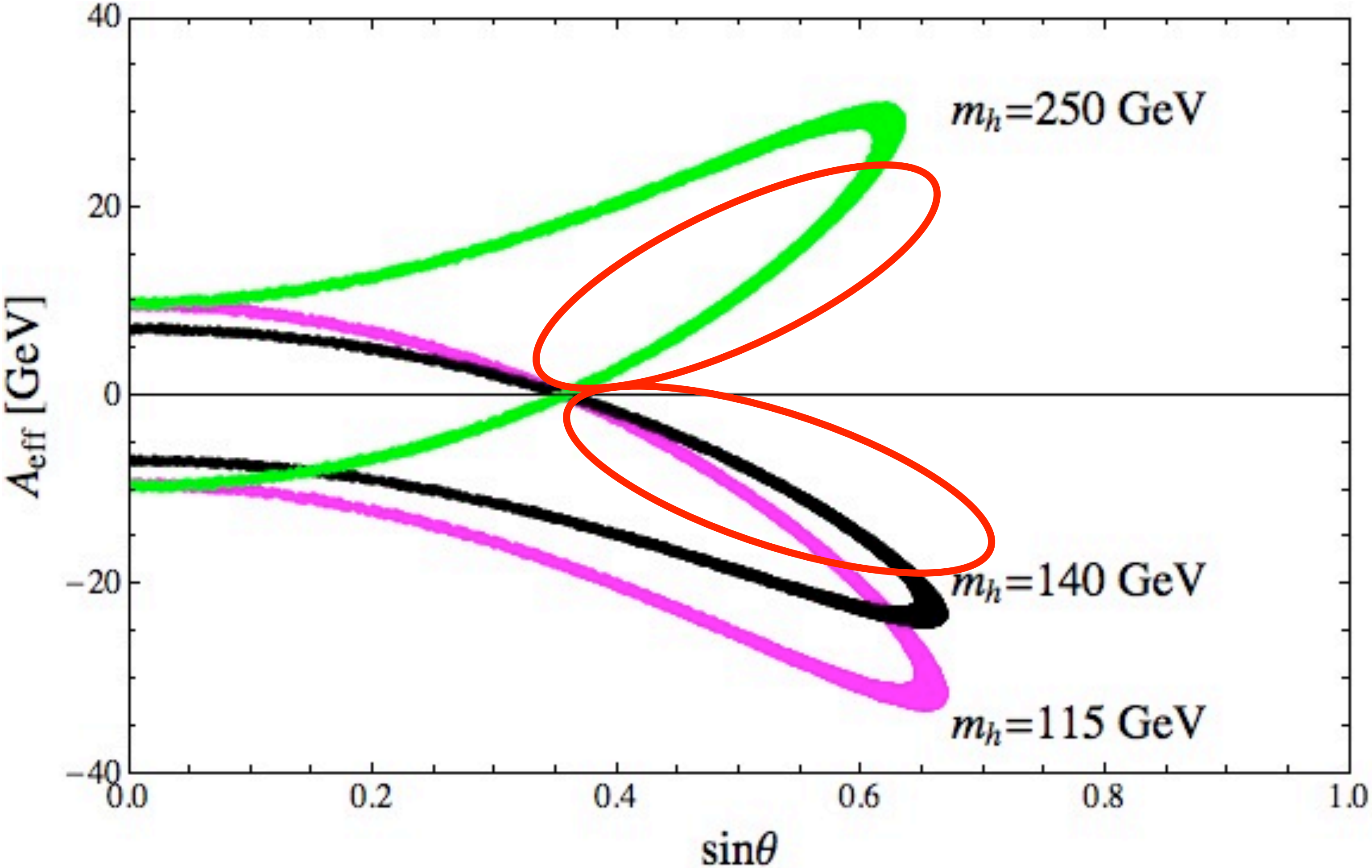


Destructive interference: Higgs exchange dominates

Dependence on $\sin\theta$

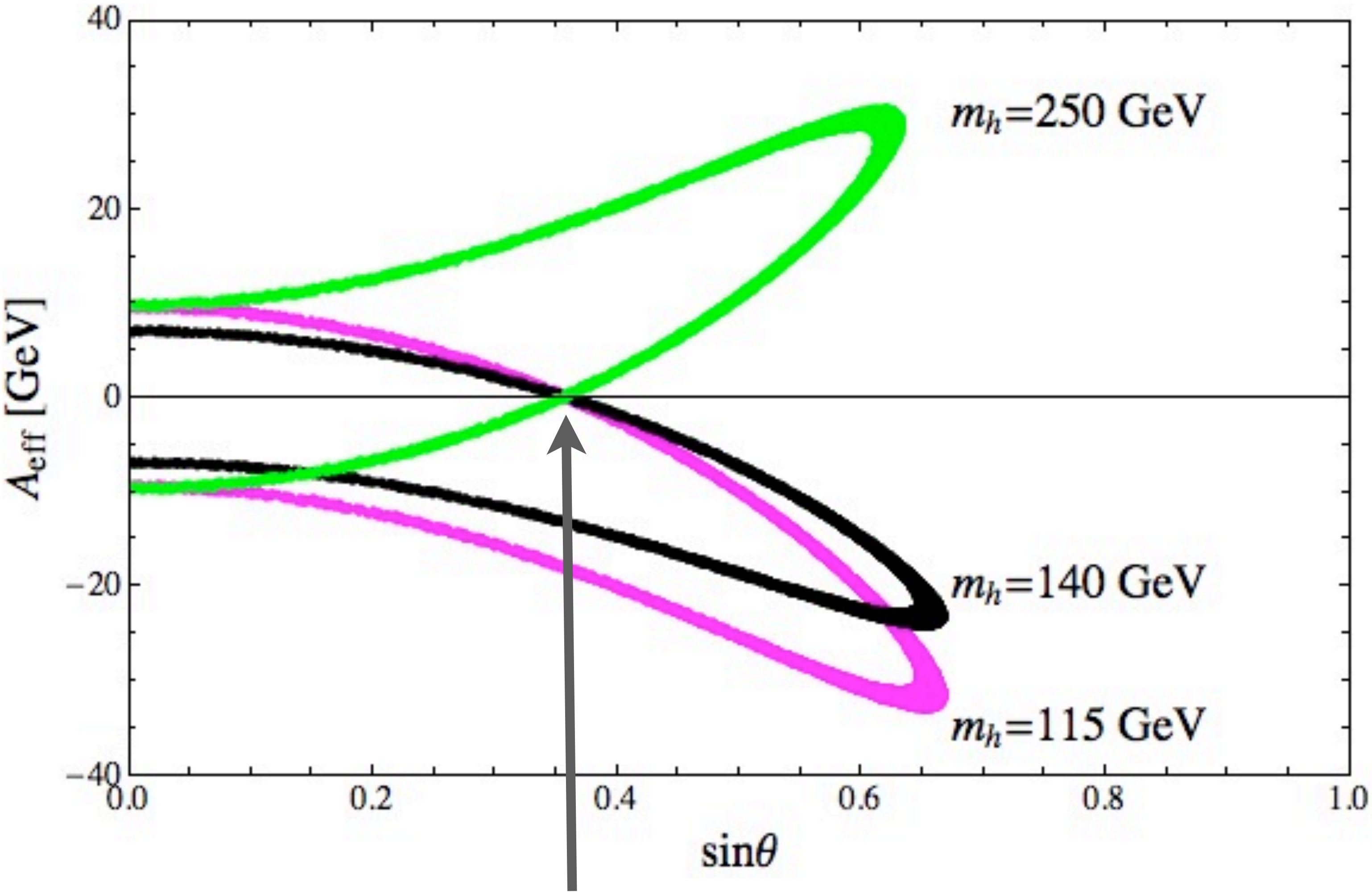


Dependence on $\sin\theta$



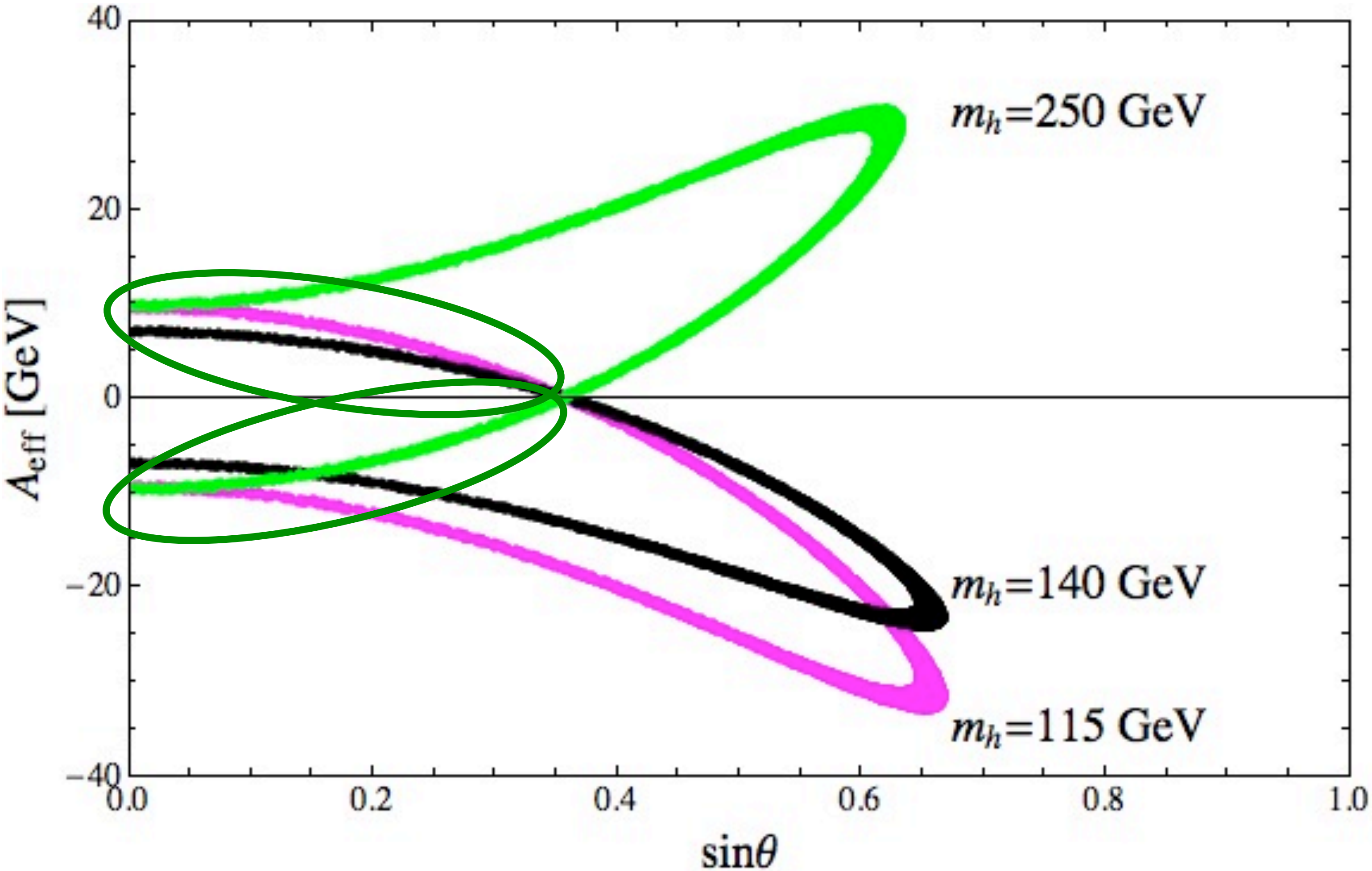
Destructive interference: 4-point dominates

Dependence on $\sin\theta$



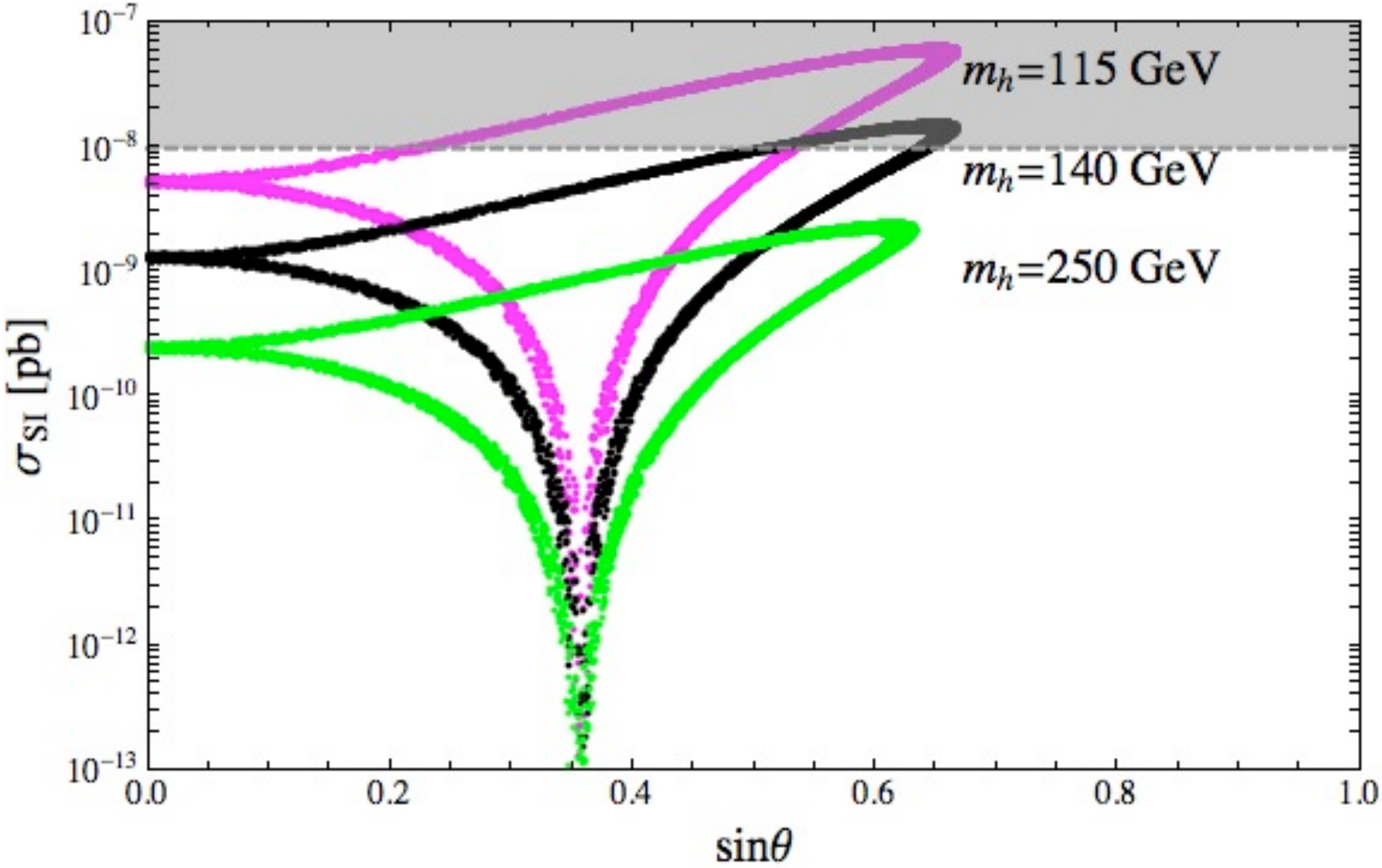
Higgs exchange vanishes.

Dependence on $\sin\theta$

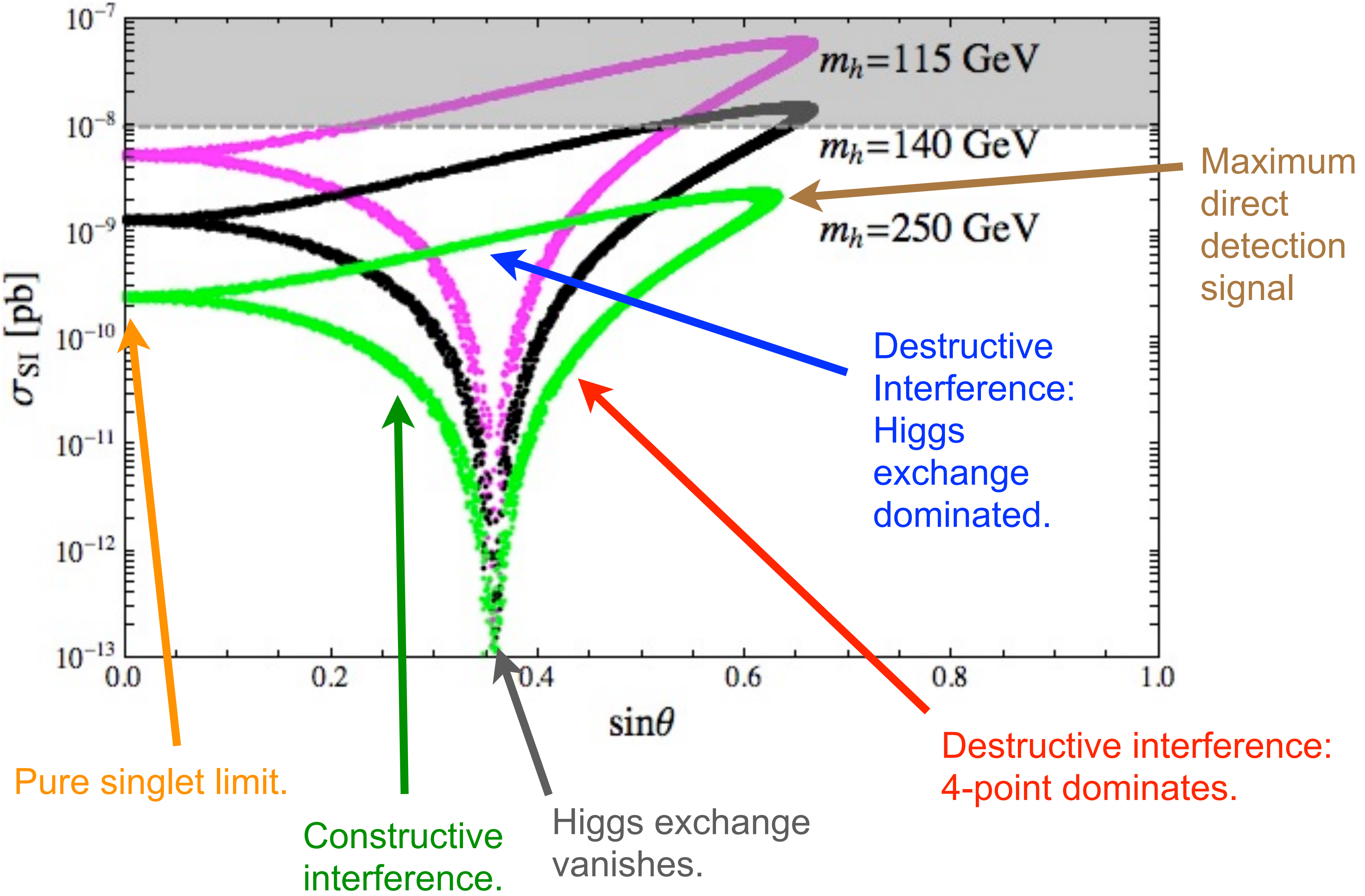


Constructive interference.

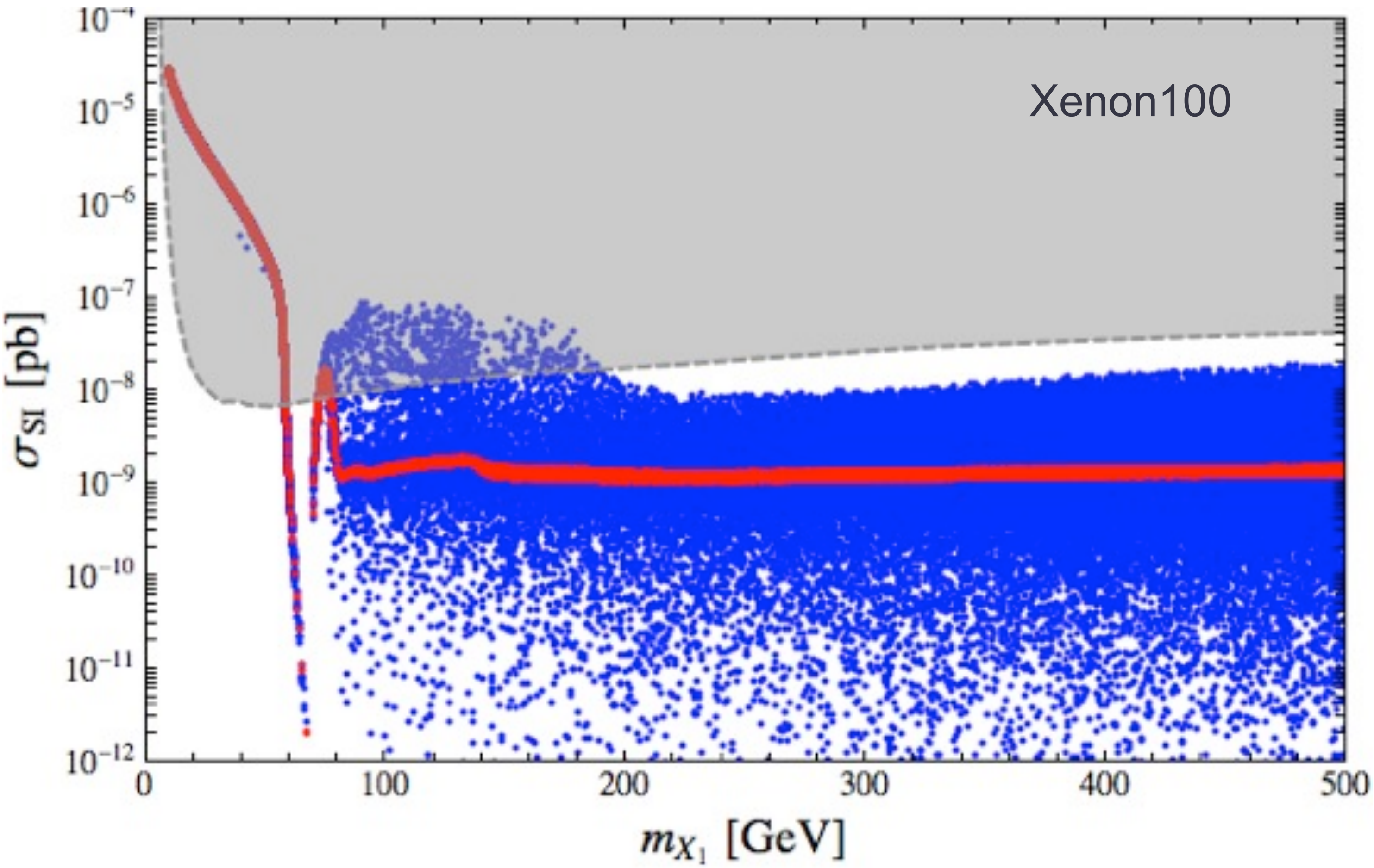
Dependence on $\sin\theta$



Dependence on $\sin\theta$



$\sigma_{\rm SI}$ versus $m_{\rm DM}$

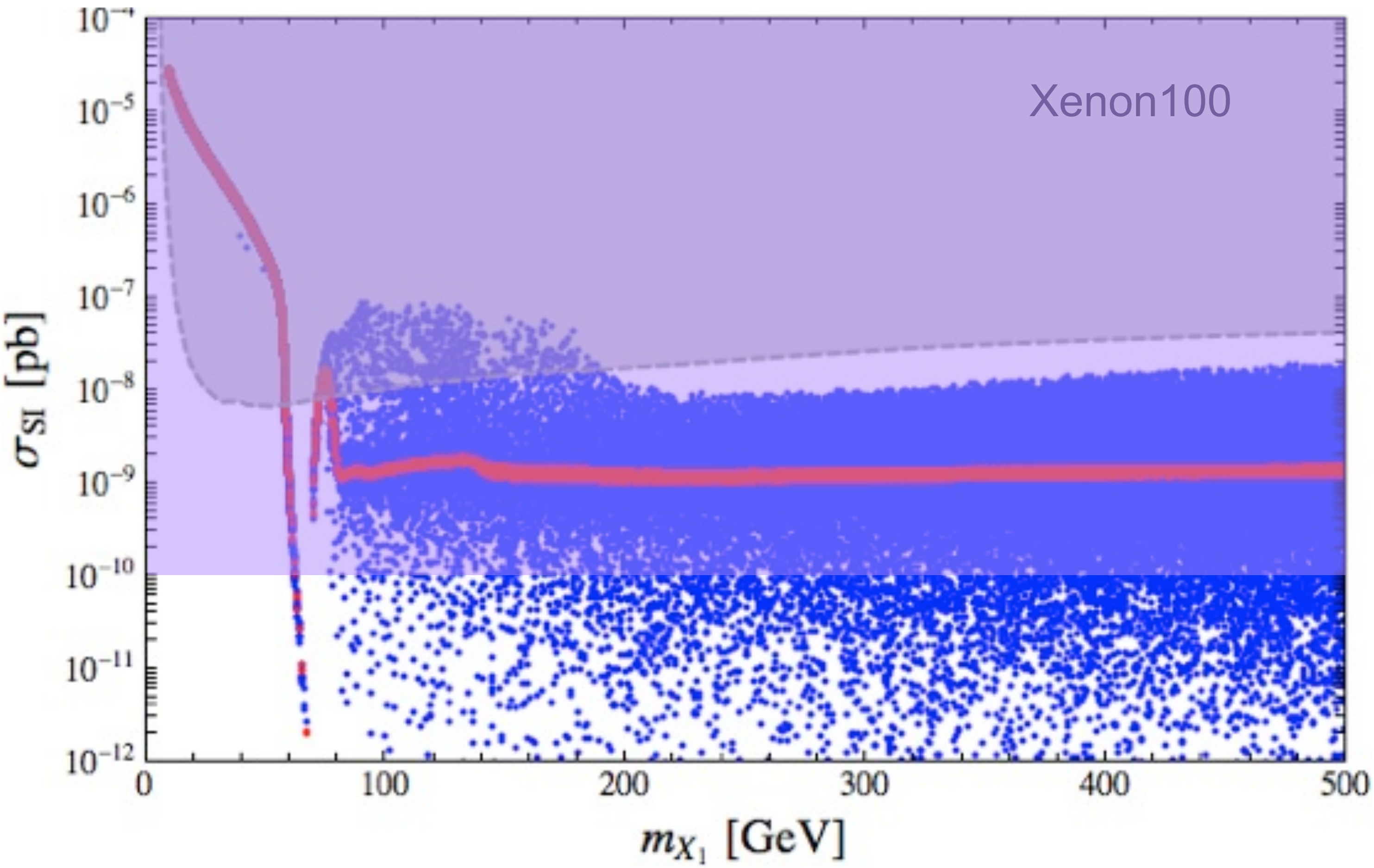


- The scan was performed over:

$$10 \text{ GeV} \leq m_{X_1} \leq 500 \text{ GeV};\ 80 \text{ GeV} \leq m_D \leq 1 \text{ TeV};\ 0 \leq g \leq v;\ |\lambda_i| \leq 1.$$

- The red points are for the pure singlet model ($\sin\theta = 0$).

$\sigma_{\rm SI}$ versus $m_{\rm DM}$



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Conclusions

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- We have explored the phenomenology of strictly weakly coupled dark matter.
- We utilized the singlet-doublet model as a proxy.
- Its annihilation, spin-independent, and spin-dependent cross sections are controlled by couplings to the $W^{\pm}$, Z, and the Higgs boson.
- Current direct detection experiments have begun to exclude some of the parameter space of these models.
- In the fermionic model, both spin-independent (e.g. Xenon 1T) and spin-dependent (e.g. DeepCore) experiments will be required to probe the remaining parameter space.
- For the scalar model, only spin-independent experiments are relevant.
- In either case, to avoid future constraints will require a tuning of the underlying parameters.

BACKUP SLIDES

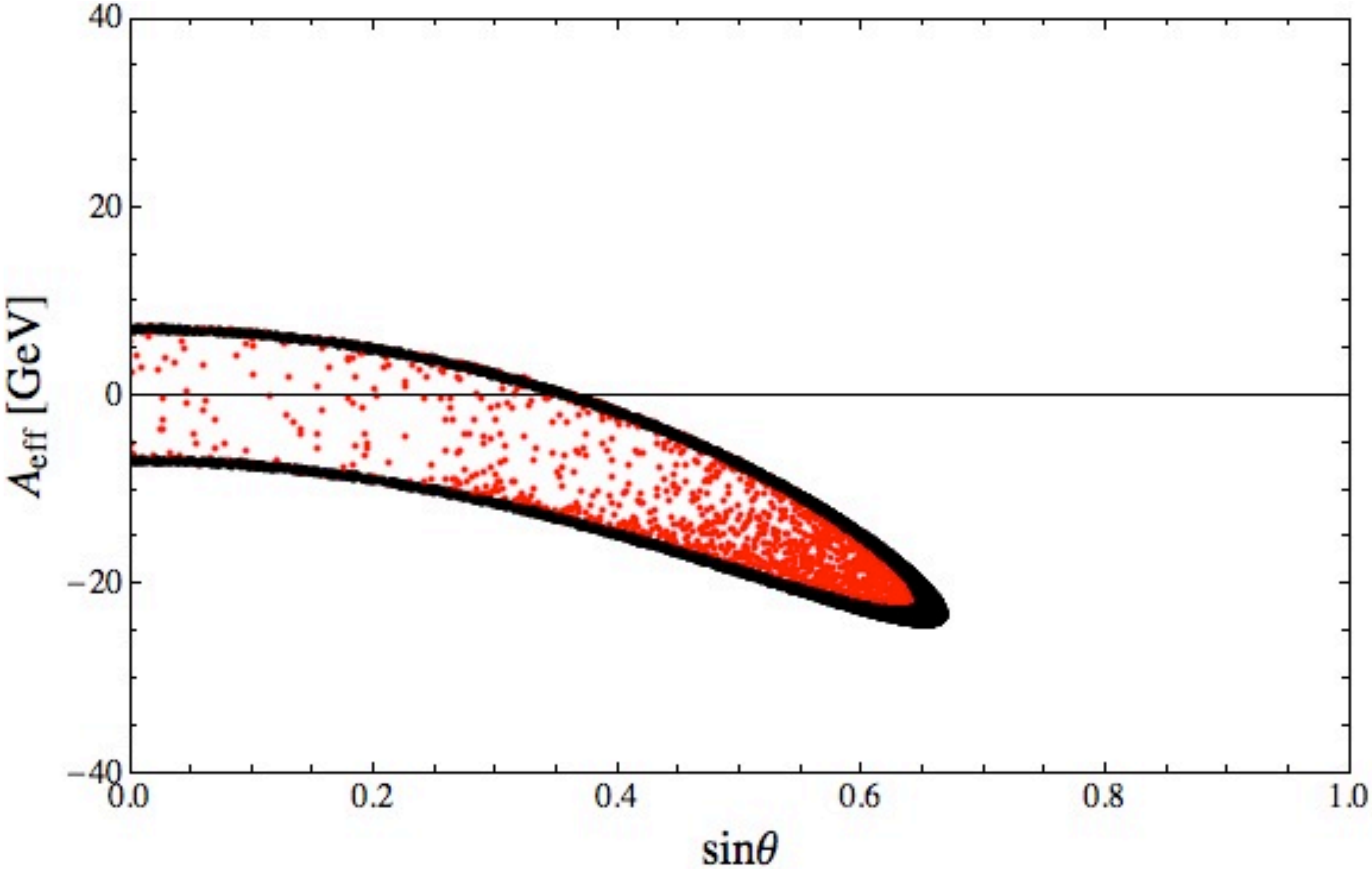
Models with an intermediate mass Higgs

- One could imagine evading the LHC Higgs mass bounds by having a non-trivial Higgs to invisible branching ratio.
- However, in the range we are interested in (e.g. ~200 GeV), one must compete with the branching ratio to W's.
- This implies large couplings between the Higgs and the dark matter.
- It is not possible to have appreciable branching ratios to the dark matter (and a thermal relic density) without violating direct detection bounds.

Cancelations in the MSSM

- The cancelations discussed above can occur in the MSSM.
- For $M_D < M_S$, the coupling to the Higgs vanishes for $\tan\beta = 1$.
- For $M_S < M_D$, the cancelation condition derived above can be translated into a condition on $\tan\beta$.
- Due to the size of the off-diagonal elements of the mixing matrix, the cancelation condition can only be satisfied for $\tan\beta \lesssim 2$.
- This is difficult to reconcile with the desire for a large Higgs mass.

Variations in the spectrum



Variations in the spectrum