ON HIGGS PORTALS TO DARK MATTER

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based on Lopez-Honorez, Schwetz, JZ, 1203.2064;
Greljo, Julio, Kamenik, Smith, JZ, 1309.3561

THE QUESTION

- Higgs is the only scalar in the SM
- can it be the (dominant) portal to dark matter?

OUTLINE

- light dark matter ($m_{DM} \lesssim m_h/2$)
  - invisible higgs decay?
- heavy dark matter ($m_{DM} \gtrsim m_h/2$)

THE MESSAGE

- for thermal relic light DM ($m_{DM} \lesssim m_h/2$)
  - Higgs portal can be the dominant coupling only if there are other new light particles

MINIMAL HIGGS PORTALS

- add to SM a single Z_2-odd neutral DM field

Patt, Wilczek, hep-ph/0605188

  - a scalar ϕ, fermion ψ, vector V_μ

$$\mathcal{H}^0_{\rm eff} = \lambda' H^\dagger H \times \phi^\dagger \phi\,,$$

$$\mathcal{H}^{1/2}_{\rm eff} = \frac{c_S}{\Lambda} H^\dagger H \times \bar\psi\psi + \frac{ic_P}{\Lambda} H^\dagger H \times \bar\psi\gamma_5\psi$$

$$\mathcal{H}^1_{\rm eff} = \epsilon_H H^\dagger H \times V^\mu V_\mu\,.$$

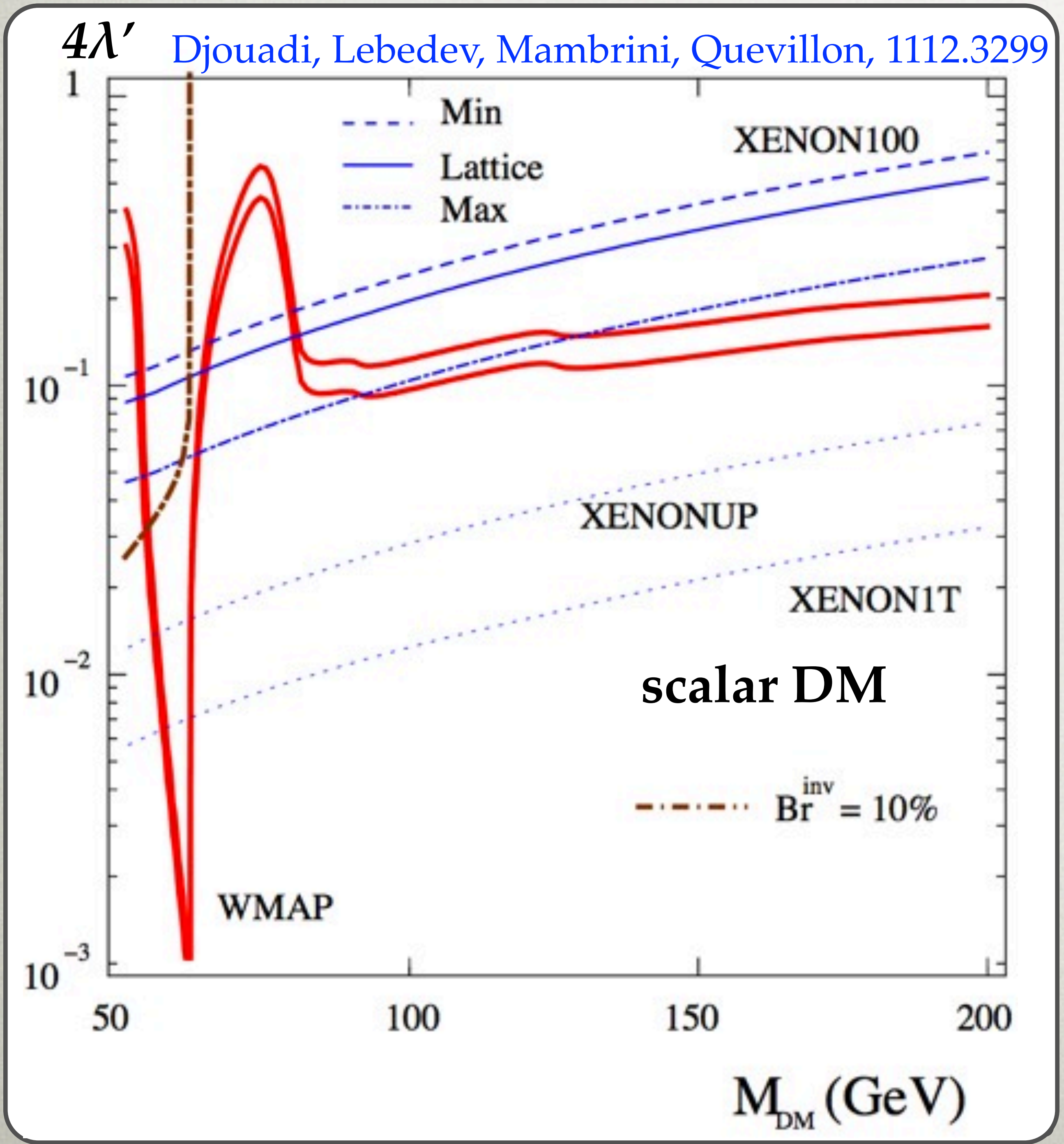
- after EWSB coupling with the Higgs

$$H^\dagger H \to \frac{1}{2}(v_{\rm EW}^2 + 2v_{\rm EW}h + h^2)$$

- minimal Higgs portal assumptions
  - that EFT expansion is valid: $\Lambda \gg v_{EW}, m_{DM}$
  - these are the dominant DM-SM interactions (early universe & collider)

LIGHT DM AND MINIMAL HIGGS PORTAL

- minimal Higgs portal excluded for light DM ($m_{DM} \lesssim m_h/2$)



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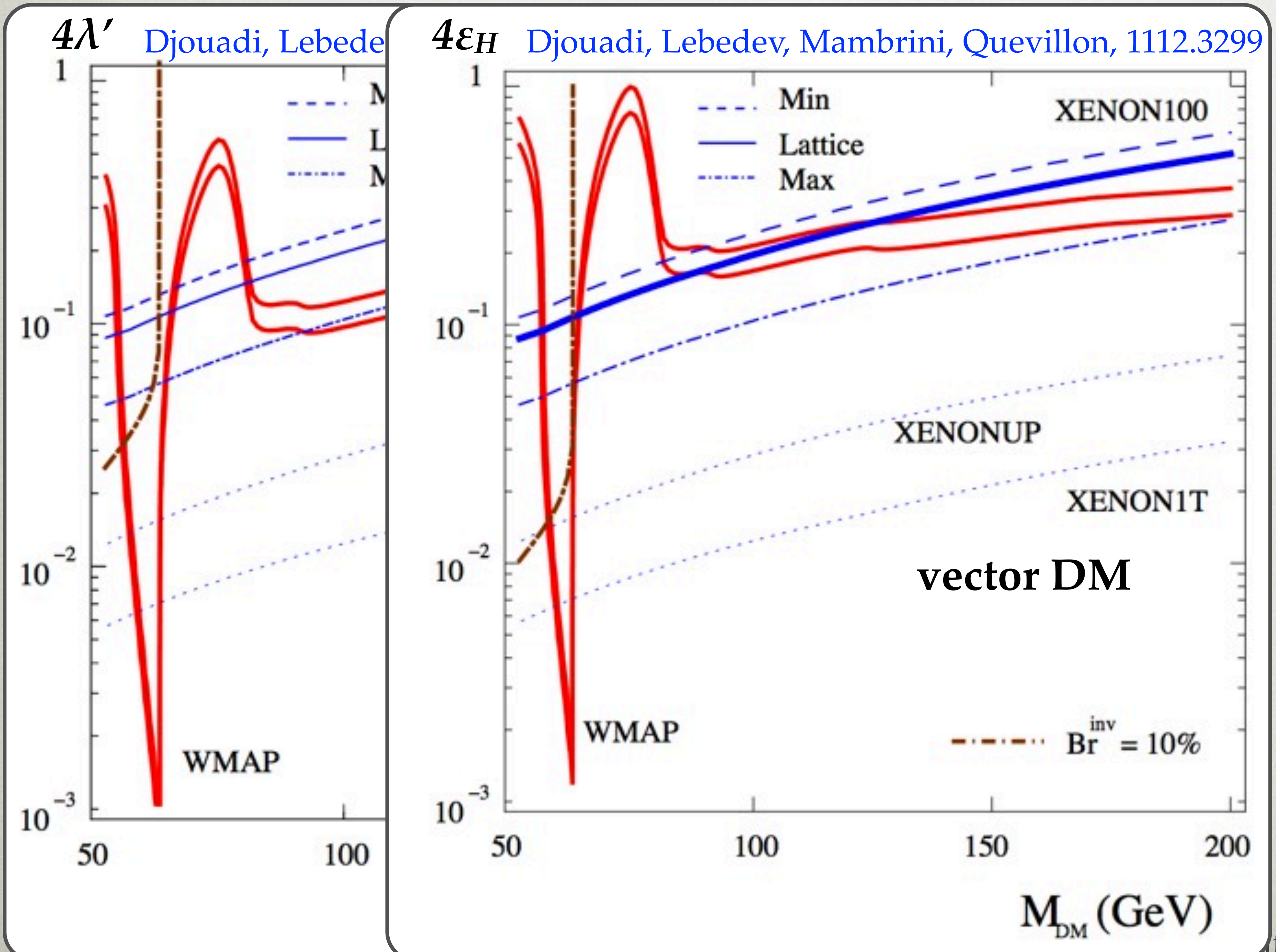

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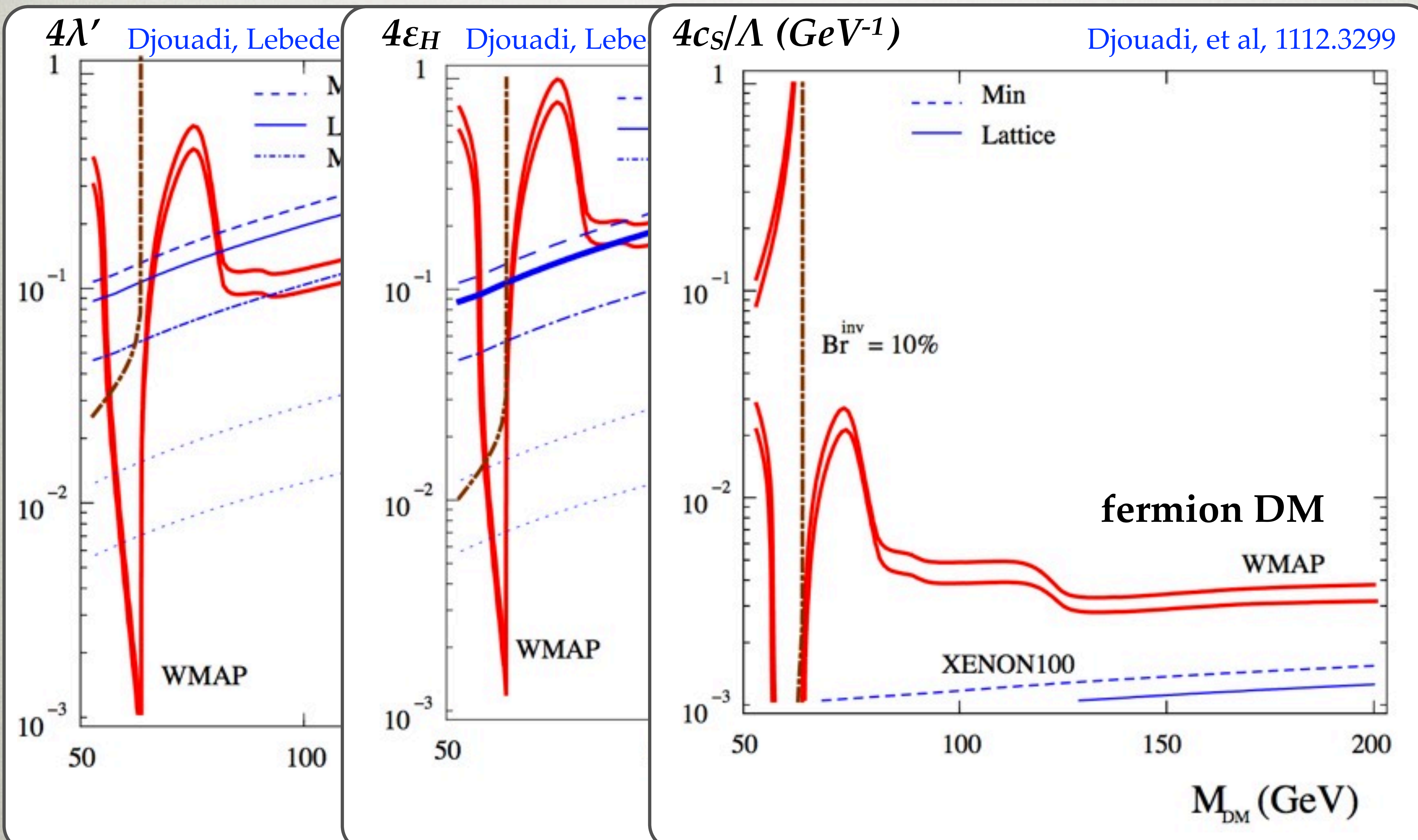


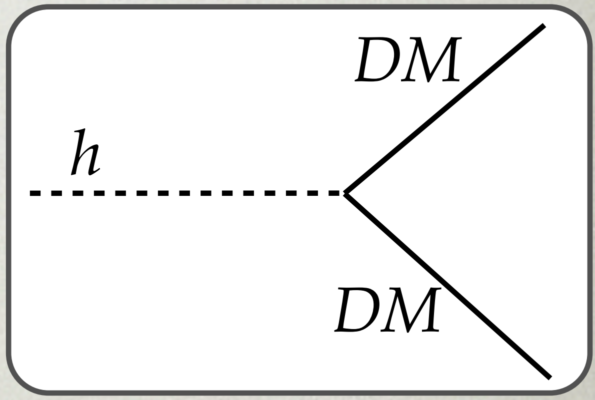
HIGHER DIM. OPERATORS

- would the situation change if v_{EW}/Λ expansion started with higher dim. ops? Greljo, Julio, Kamenik, Smith, JZ, 1309.3561
- first perform NDA
  - canonical dim. $d=4+n$ of the relevant interact. operator

$$H_{\text{eff}} = \frac{c_n}{\Lambda^n} O_n + \cdots$$

- for $m_{DM} \ll m_h/2$ the invisible Higgs Br

$$\mathcal{B}(h \to \text{invisible}) \sim 10^3 \left(\frac{m_h}{\Lambda}\right)^{2n}$$



  - the normalization $10^3 \sim 1/y_b^2$ from Higgs Γ_{tot}
  - assumes all c~$O(1)$
  - two body $h \to inv.$ kinematics

DIRECT DETECTION AND HIGHER DIM. OPERATORS

- current constraints from direct DM detection experiments

$$\frac{\langle \sigma_{\rm dir} \rangle}{\langle \sigma_{\rm dir} \rangle_{\rm excl.}} \sim 10^2 \left(\frac{m_h}{\Lambda}\right)^{2n} \left(\frac{m_{\rm DM}}{m_h}\right)^{m} \beta^{2m'}$$

  - assumes SI scattering (constr. stronger than for SD)
  - numerical factor due to XENON100/LUX bound
    - will increase in the future
  - m_{DM}/m_h and DM velocity $\beta \sim 10^{-3}$ suppressions are operator dependent, but always ≤1
  - the m_h/Λ suppression the same as in $Br(h\to inv.)$
- at present $h\to inv.$ stronger constr. for light DM than direct DM detection for any operator dimension

THERMAL RELIC

- if DM is a thermal relic

$$\langle \sigma_{\rm ann} v \rangle \sim \frac{y_f^2}{32\pi} \left(\frac{m_h}{\Lambda}\right)^{2n} \left(\frac{m_{\rm DM}}{m_h}\right)^k m_h^2$$

  - here $k \geq k_{min}=0(2)$ for scalar/vector (fermion)
  - the scaling with Λ the same as for $Br(h \to inv.)$

$$\left(\frac{\mathcal{B}_h^{\rm invis.}}{\langle \sigma_{\rm ann.} v \rangle}\right)_n \sim \left(\frac{m_h}{m_{\rm DM}}\right)^{k-k_{\rm min}} \left(\frac{\mathcal{B}_h^{\rm invis.}}{\langle \sigma_{\rm ann.} v \rangle}\right)_{n_{\rm min}}$$

- since $k \geq k_{min}$ the Higgs constraints only become stronger for higher dim. operator
- based on NDA higher dim. ops. cannot reconcile Higgs portal DM with $Br(h \to inv.)$ constraints

UNDERLYING ASSUMPTIONS

- *Br(h→inv.)* places strong constraints on Higgs portal DM
- underlying assumptions
    - that *h→DM DM* decay is possible
    - *h* is the only light new particle
    - Higgs couplings to the fermions are the SM ones

SUPPRESSING INVISIBLE HIGGS DECAY

Greljo, Julio, Kamenik, Smith, JZ, 1309.3561

- three possibilities to suppress $h \to DM+DM$
  - *DM* annihilation not predominantly through ops. involving Higgs
    - orthogonal to the Higgs portal idea
  - kinematically forbidden because DM is heavy, $m_{DM} > m_h/2$
  - if the dominant oper. such that $h \to DM+DM$ forbidden, but $h \to DM+DM+X_{SM}$ allowed
    - will work in EFT
    - set aside model building of how this arises
    - go through the list of lowest dim. operators

HIGGS VECTOR CURRENT

- the simplest that $h \to DM + DM + X_{SM}$ from Higgs vector current

$$H^\dagger \overleftrightarrow{D}^\mu H \equiv H^\dagger \overleftarrow{D}^\mu H - H^\dagger \overrightarrow{D}^\mu H \to \frac{ig}{2c_W}(v_{\rm EW}^2 + 2v_{\rm EW} h + h^2) Z^\mu$$

- the ops. of lowest dimension

$$\mathcal{H}_{\rm eff}^0 = \frac{c_\phi}{\Lambda^2} H^\dagger \overleftrightarrow{D}_\mu H \times \phi^\dagger \overleftrightarrow{\partial}^\mu \phi \,,$$
$$\mathcal{H}_{\rm eff}^{1/2} = \frac{c_\psi^V}{\Lambda^2} i H^\dagger \overleftrightarrow{D}_\mu H \times \bar\psi \gamma^\mu \psi + \frac{c_\psi^A}{\Lambda^2} i H^\dagger \overleftrightarrow{D}_\mu H \times \bar\psi \gamma^\mu \gamma_5 \psi \,,$$
$$\mathcal{H}_{\rm eff}^1 = \frac{c_V}{\Lambda^2} i H^\dagger \overleftrightarrow{D}_\nu H \times V_\mu \overleftrightarrow{\partial}^\nu V^\mu \,.$$

- induce a 3-body decay $h \to DM + DM + Z$ but not $h \to DM + DM$
  - allowed for $m_{DM} < (m_h - m_Z)/2 \simeq 17 GeV$
  - excluded by LEP $Z \to E_{miss}$ measrmnts, except for fermionic DM with vector int. and $14 GeV < m_{DM} < 17 GeV$
  - this excluded by direct DM detection

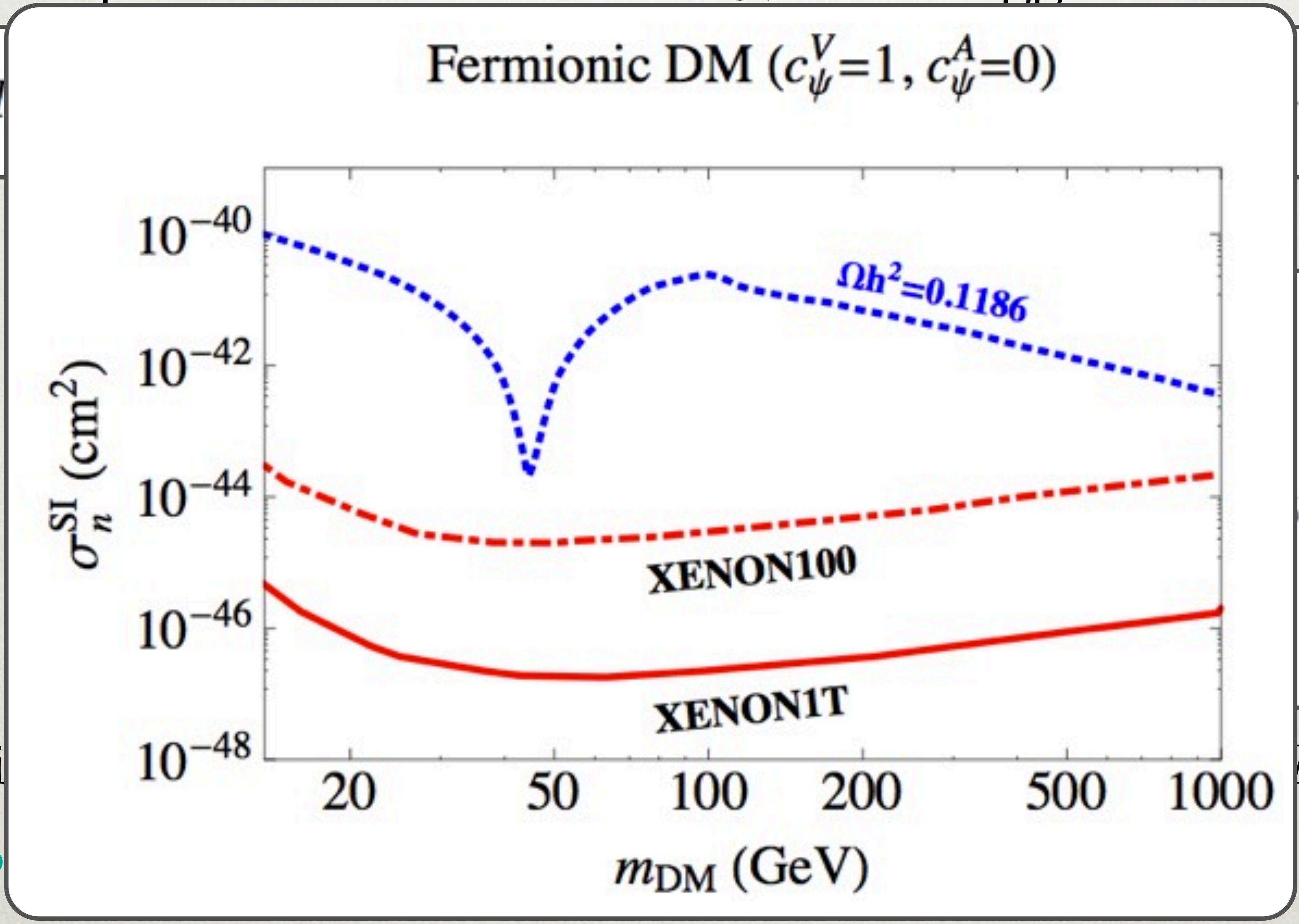
HIGGS VECTOR CURRENT

- the simplest that $h \to DM+DM+X_{SM}$ from Higgs vector current

H ... $h^2)Z^\mu$

- the

... ψ ,



- i ... $M+DM$
  -
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SCALAR AND TENSOR CURRENTS

- lowest dim. ops

$$\mathcal{H}_{\rm eff}^{0} = \frac{f_\phi}{\Lambda^2}\Gamma^S \times \phi^\dagger\phi \ + h.c.,$$
$$\mathcal{H}_{\rm eff}^{1/2} = \frac{f_\psi^S}{\Lambda^3}\Gamma^S \times \overline{\psi}\psi + \frac{f_\psi^P}{\Lambda^3}\Gamma^S \times i\overline{\psi}\gamma_5\psi + \frac{f_\psi^T}{\Lambda^3}\Gamma^T_{\mu\nu} \times \overline{\psi}\sigma^{\mu\nu}\psi \ + h.c.,$$
$$\mathcal{H}_{\rm eff}^{1} = \frac{f_V}{\Lambda^2}\Gamma^S \times V_\mu V^\mu \ + h.c.,$$

$$\Gamma^S = H^\dagger \bar{D} Q,\ \ H^\dagger \bar{E} L,\ \ H^{*\dagger}\bar{U} Q, \quad \Gamma^T_{\mu\nu} = H^\dagger \bar{D}\sigma_{\mu\nu} Q,\ \ H^\dagger \bar{E}\sigma_{\mu\nu} L,\ \ H^{*\dagger}\bar{U}\sigma_{\mu\nu} Q\ .$$

- f_i couplings taken to be the SM yukawas
- would give small Higgs Br, e.g. Br($h \to DM+DM+bb$)~10^{-7}
- DM detection bounds:
  - exclude all interactions except $f_\psi{}^T$ and $f_\psi{}^P$ for fermionic DM
- also not excluded by Fermi-LAT

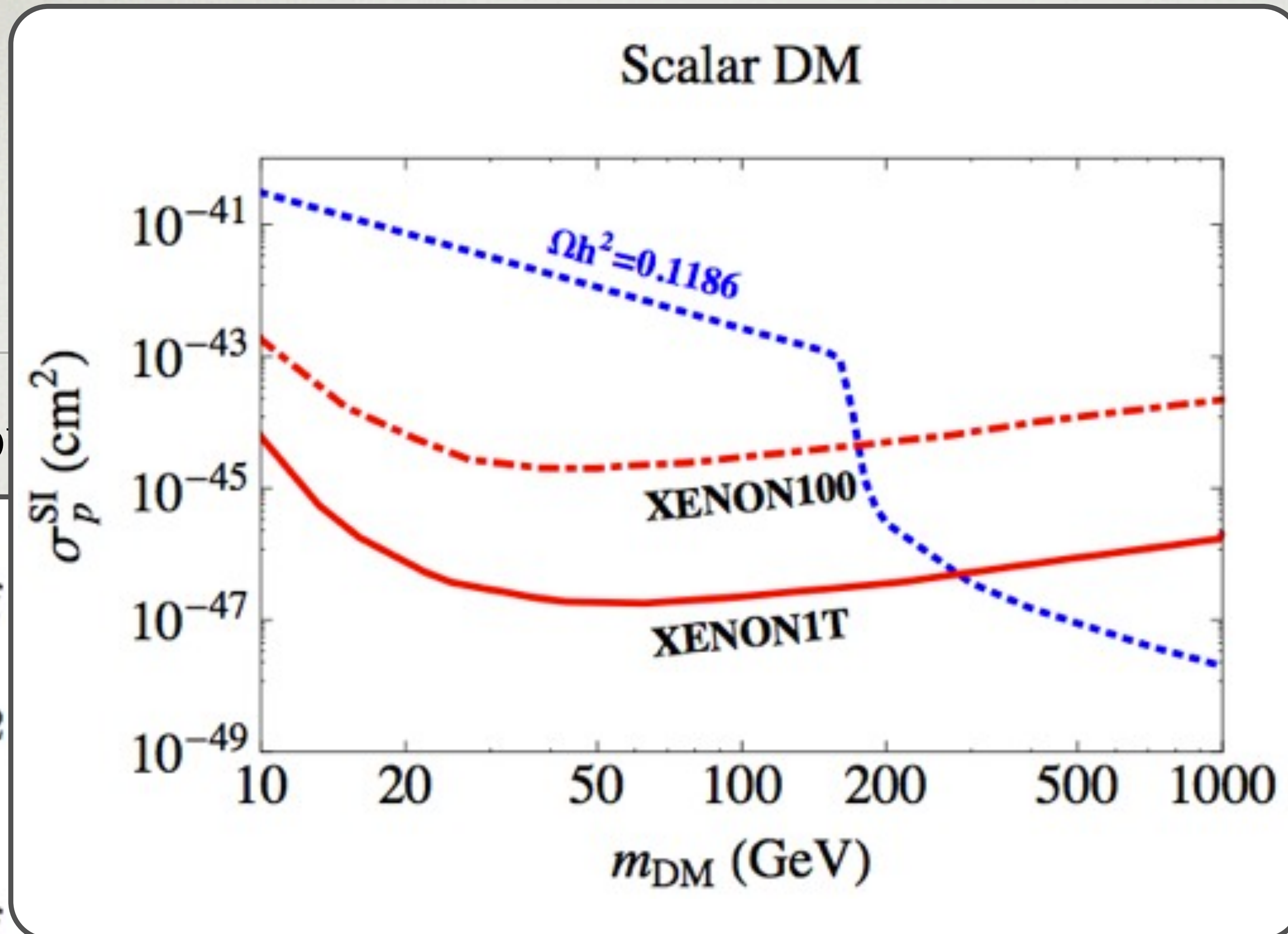
...SOR

- lo...

$$\mathcal{H}_{\rm eff}^{0} \ldots$$

$$\mathcal{H}_{\rm eff}^{1/2} \ldots \sigma^{\mu\nu}\psi + h.c.,$$

$$\mathcal{H}_{\rm eff}^{1} \ldots \Lambda^2$$



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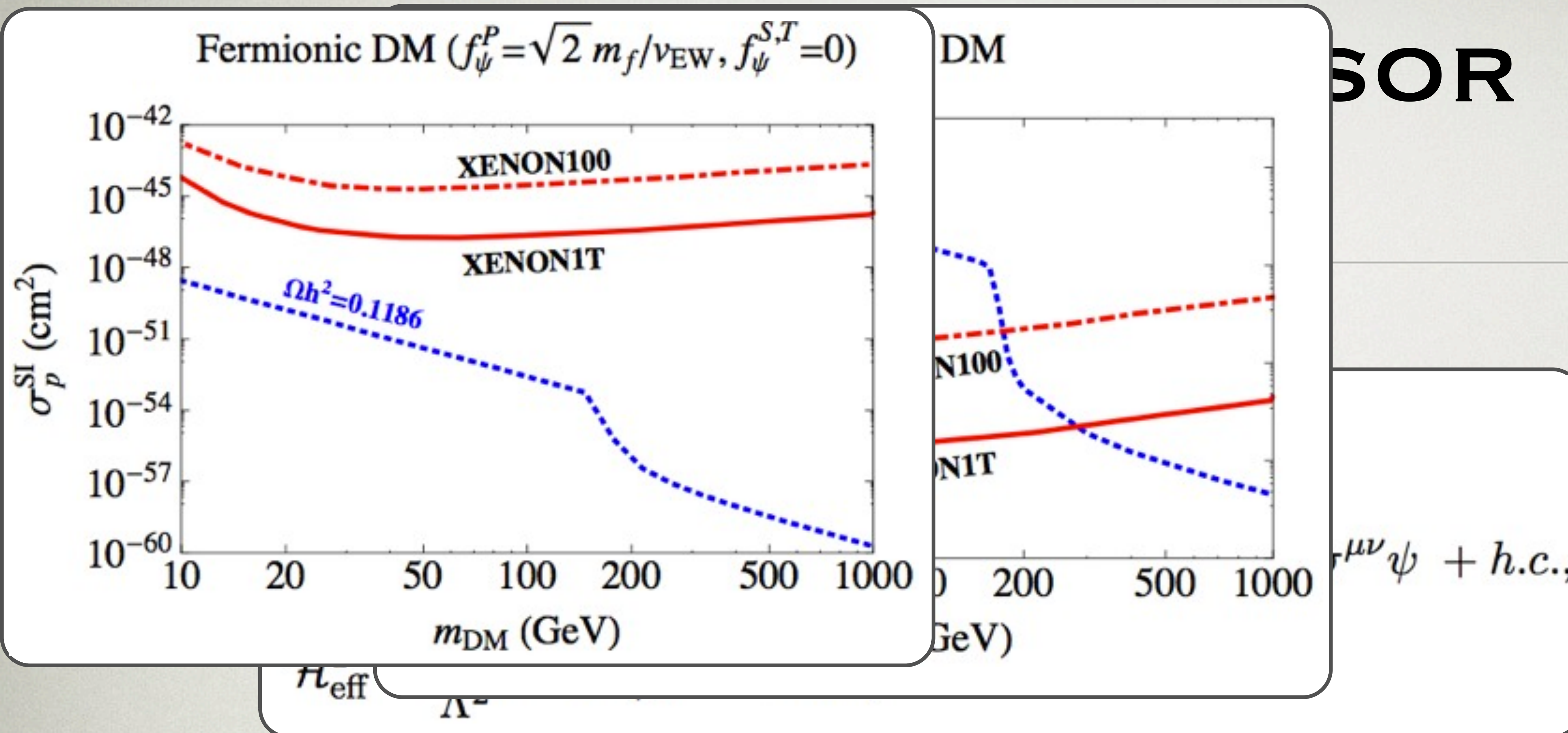

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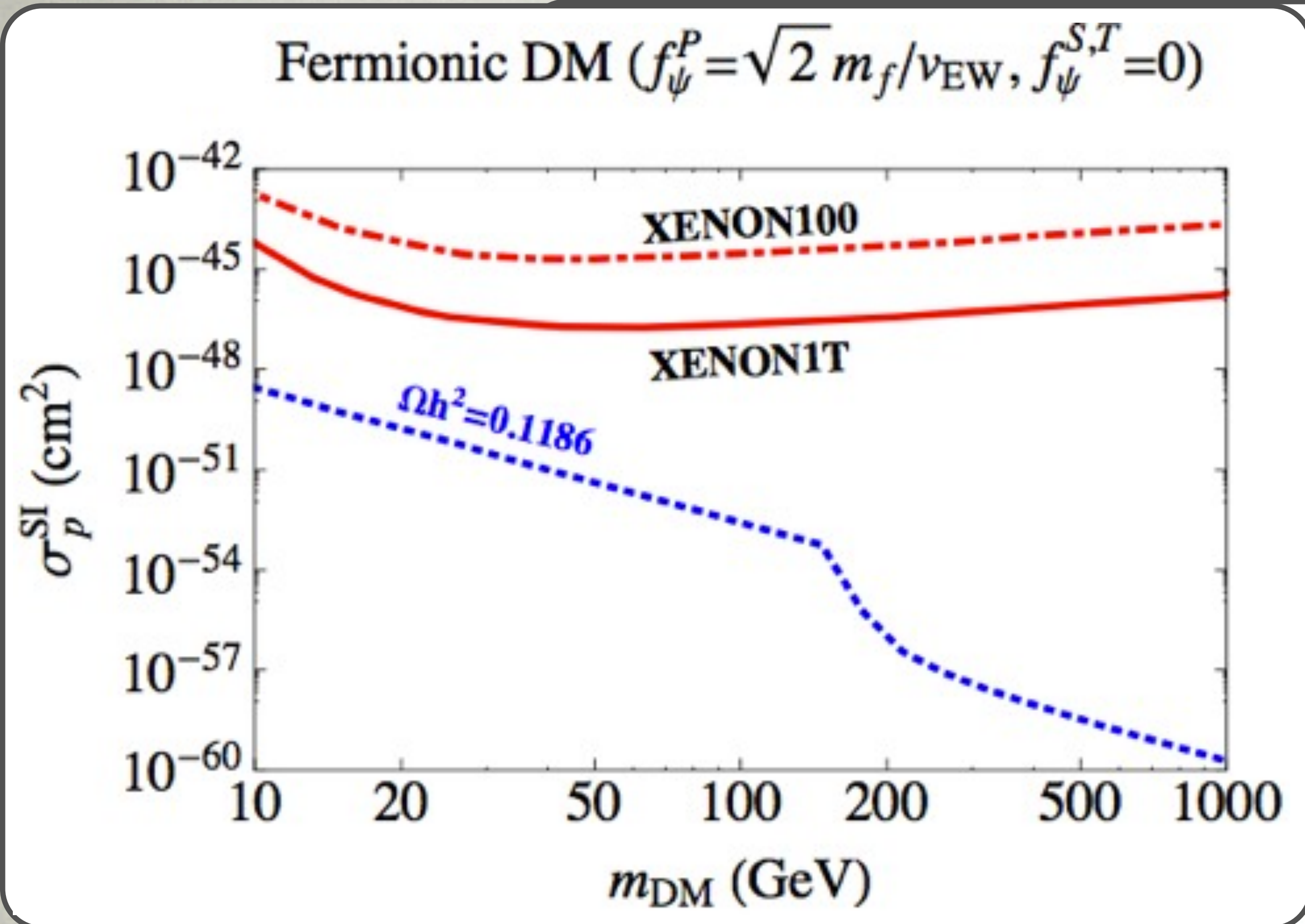

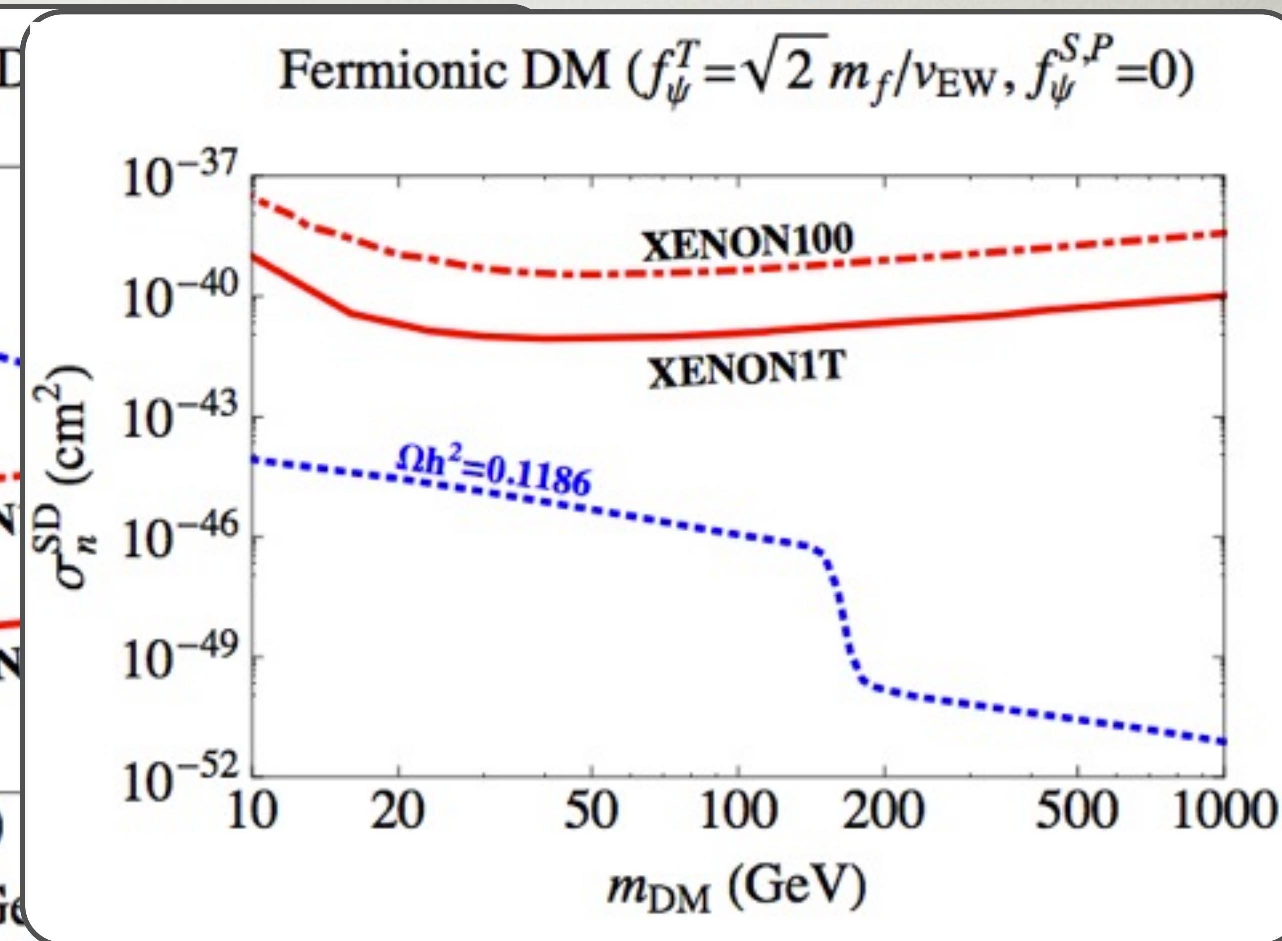

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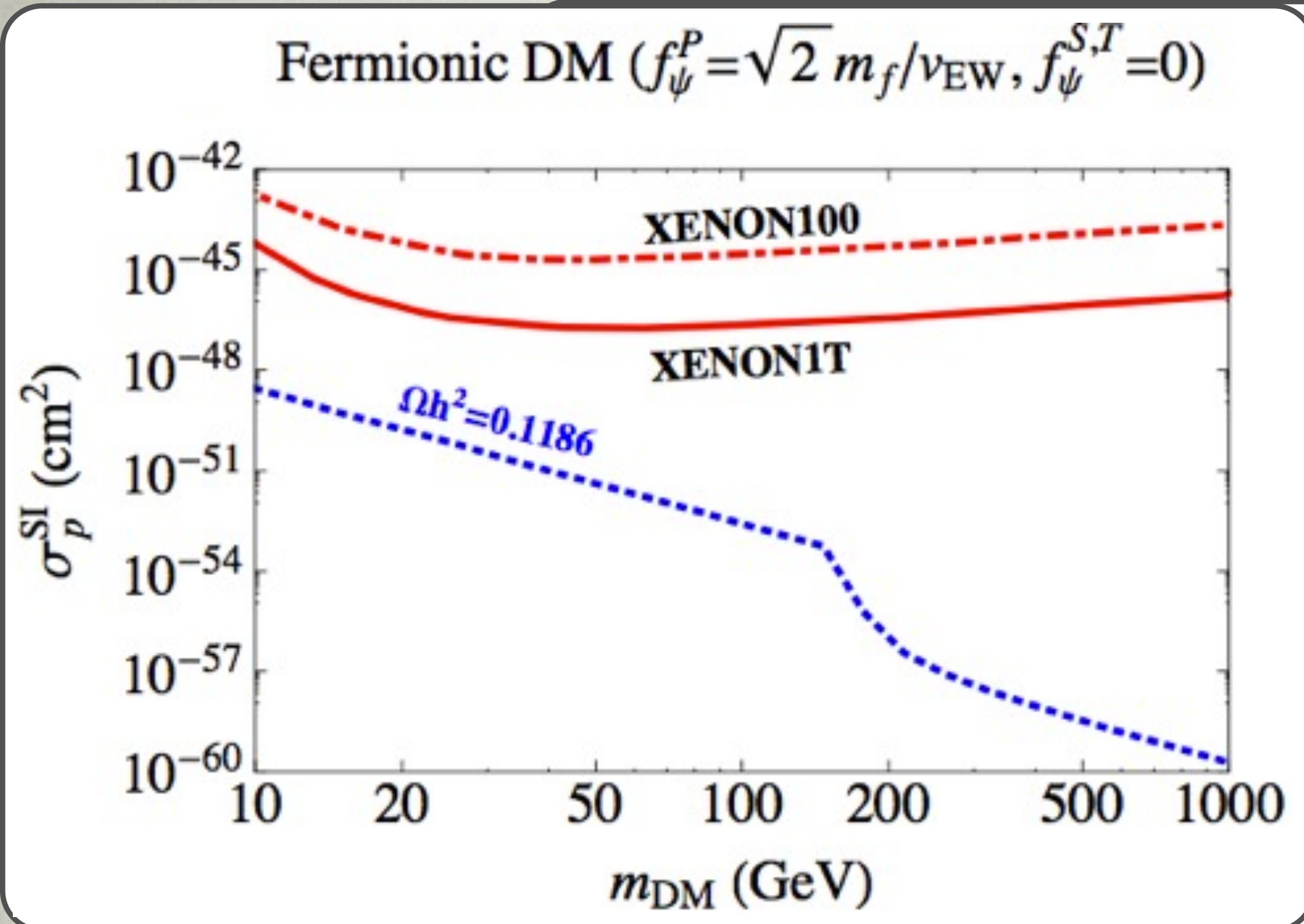
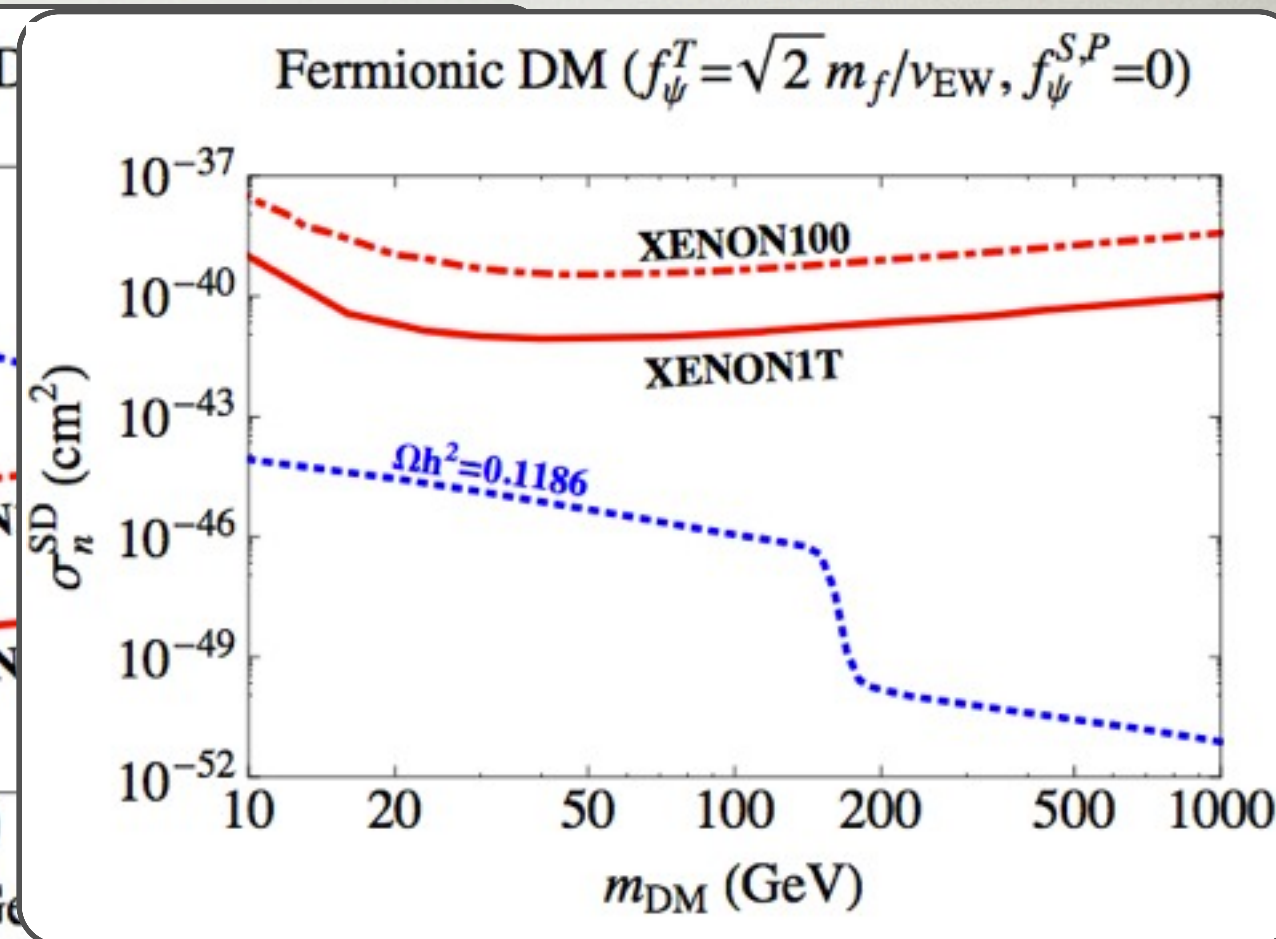

Fermionic DM ($f_\psi^P=\sqrt{2}\,m_f/v_{EW}$, $f_\psi^{S,T}=0$)
XENON100
XENON1T
$\Omega h^2=0.1186$
σ_p^{SI} (cm^2)
m_{DM} (GeV)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XENON100
XENON1T
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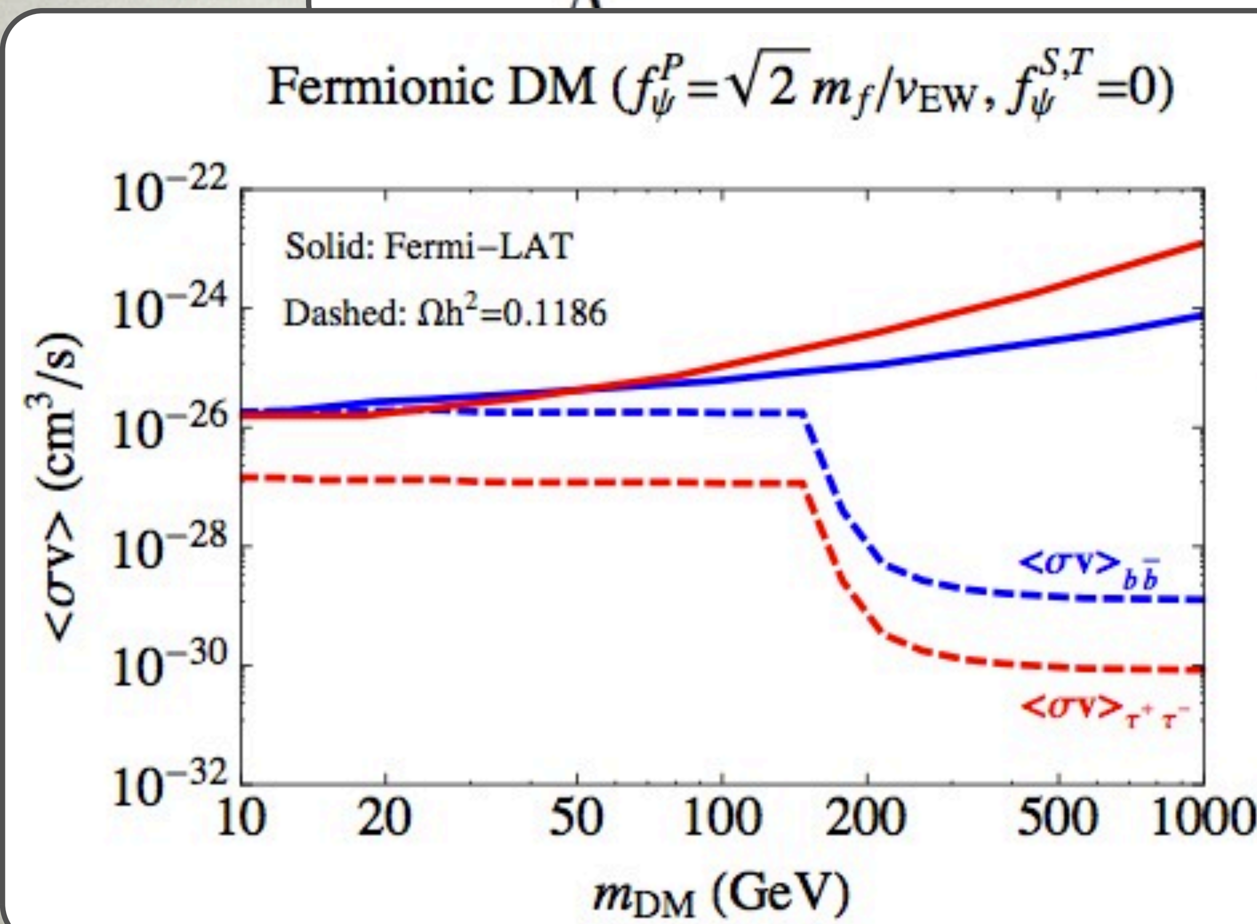
σ_n^{SD} (cm^2)
m_{DM} (GeV)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Solid: Fermi−LAT
Dashed: $\Omega h^2=0.1186$
$\langle\sigma v\rangle_{b\bar{b}}$
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$\langle\sigma v\rangle$ (cm^3/s)
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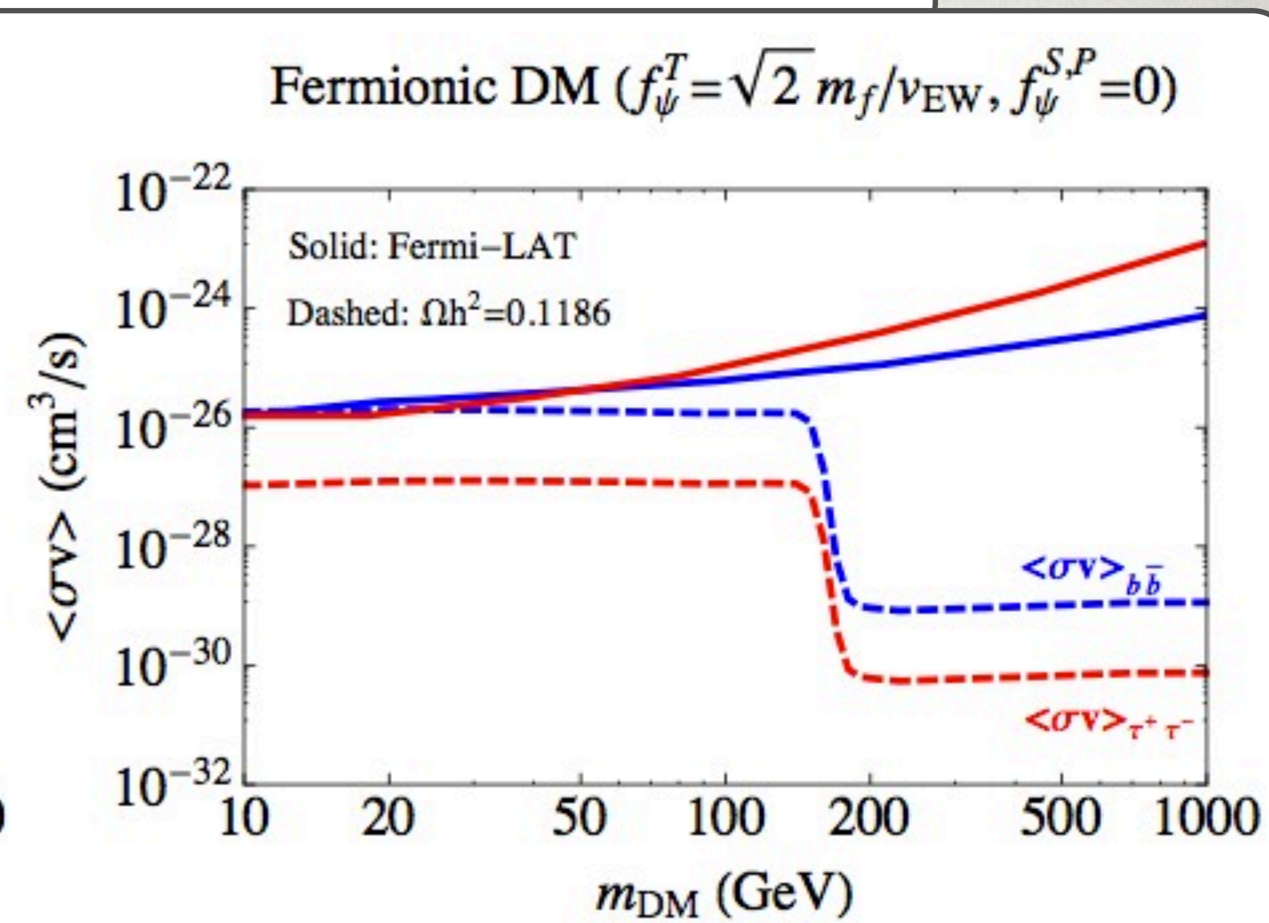
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$\langle\sigma v\rangle_{b\bar{b}}$
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$\langle\sigma v\rangle$ (cm^3/s)
m_{DM} (GeV)

WEINBERG-LIKE OPERATOR

- completely invisible Higgs decay from

$$L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \times \mathcal{O}_{\rm dark},$$

$$\mathcal{H}^0_{\rm eff} = \frac{g_\phi}{\Lambda^3} L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \times \phi^\dagger \phi,$$

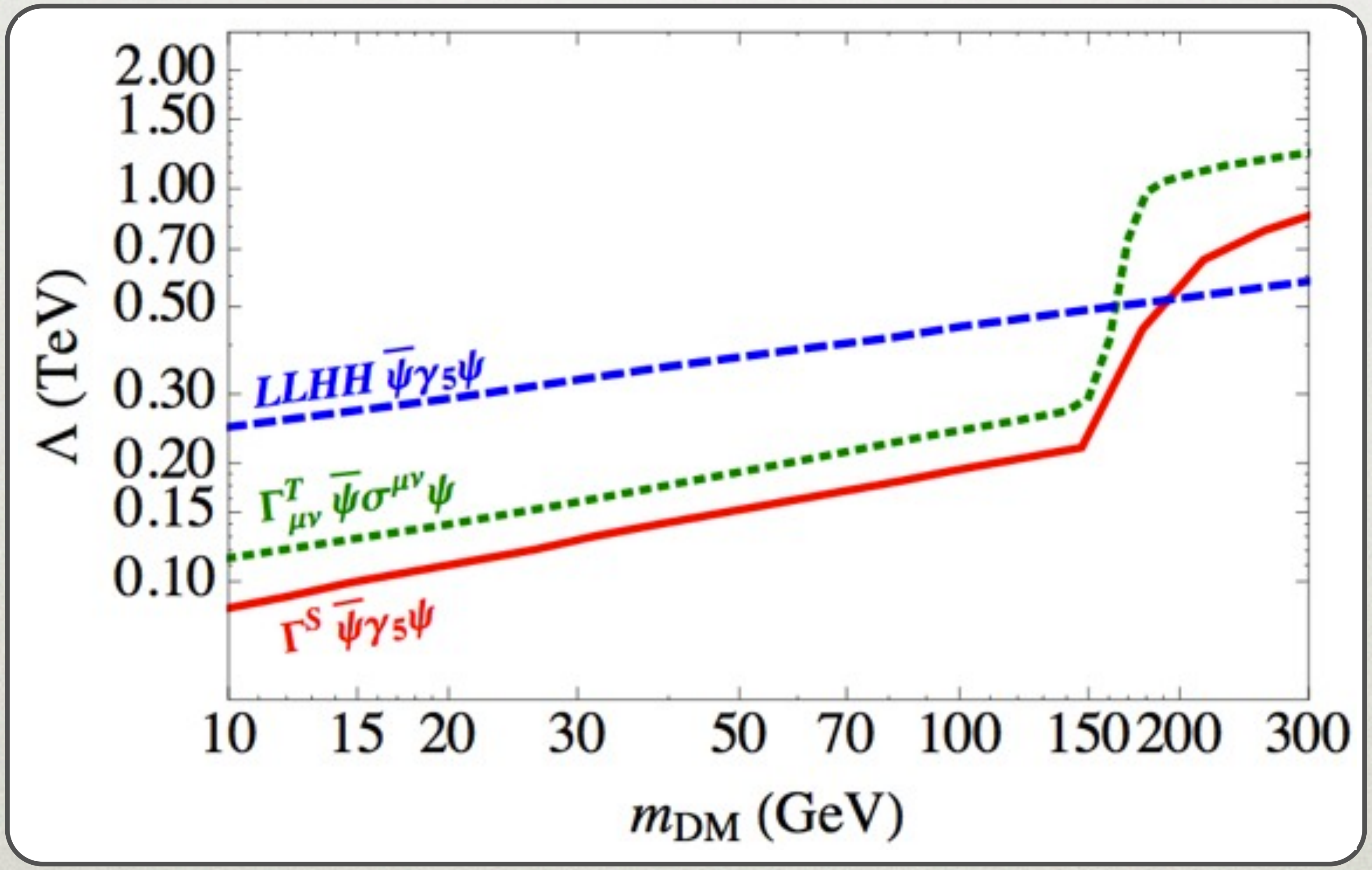
$$\mathcal{H}^{1/2}_{\rm eff} = \frac{g^S_\psi}{\Lambda^4} L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \times \overline{\psi}\psi + \frac{g^P_\psi}{\Lambda^4} L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \times i\overline{\psi}\gamma_5\psi,$$

$$\mathcal{H}^1_{\rm eff} = \frac{g_V}{\Lambda^3} L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \times V_\mu V^\mu,$$

- all except $g_\psi{}^P$ lead to ν masses at 1-loop
- for $g_\psi{}^P$ with correct relic DM abundance: $Br(h\rightarrow DM+DM+\nu\bar{\nu})\sim 10^{-7}$

LOW SCALE

- all the surviving operators have low scale for correct DM density



- ⇒ ∃ extra new light particles

VIABLE HIGGS PORTAL MODELS

- EFT analysis:
  - Higgs portal DM models need to have more new particles beyond just DM
- three concrete examples
  - two that match onto EFT
    - leptophilic model ⇒ Weinberg-like oper.
    - type II 2HDM+scalar DM⇒scalar Higgs current oper
  - one that violates EFT
    - SM+scalar DM+ extra scalar lighter than DM

LEPTOPHILIC MODEL

- SM+Dirac fermion DM ψ+triplet scalar Δ+singlet scalar ϕ

$$\psi \sim (1,1,0), \quad \phi \sim (1,1,0), \quad \Delta \sim (1,3,1).$$

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

- the terms that generate Winberg-like operator are

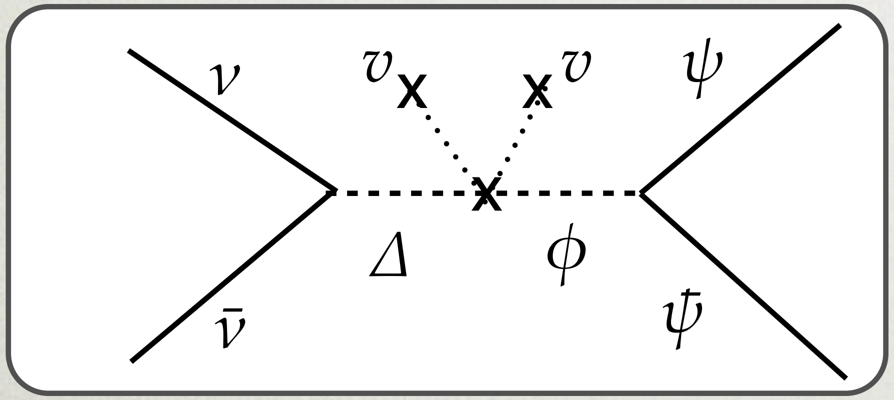
$$\mathcal{L} \supset -\frac{m_\phi^2}{2}\phi^2 - m_\Delta^2 \mathrm{Tr}\Delta^\dagger\Delta - m_{\rm DM}\bar{\psi}\psi + \left[iy\bar{\psi}\gamma_5\psi\phi + \lambda\phi H^i H^j \epsilon_{ik}\Delta^*_{jk} + f_{ab}L^i_a L^j_b \epsilon_{ik}\Delta_{kj} + \mathrm{h.c.}\right]$$

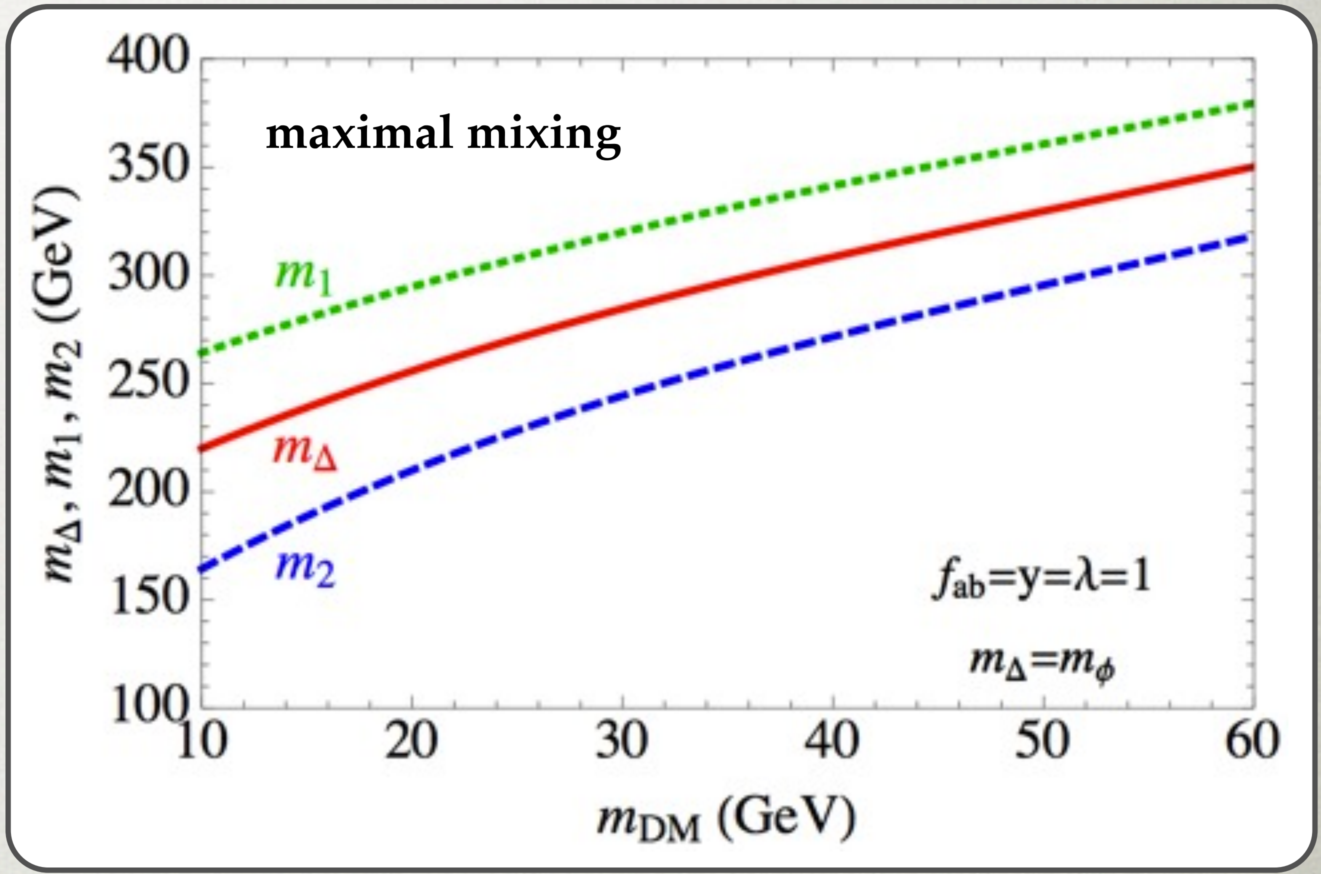
- from which one obtains after integrating out Δ, ϕ

$$L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \times i\overline{\psi}\gamma_5\psi$$

LEPTOPHILIC MODEL

- the $h \to inv.$ and $DM\ DM \to X_{SM}$ are now decoupled
- the correct relic density from $\psi\bar{\psi} \to \nu\bar{\nu}$
  - requires significant ϕ-Δ^0 mixing
  - note: does not proceed through h resonance





- to avoid $h \to inv.$ bounds (and direct DM detect. in the future)
  - need to suppress ϕ-h mixing
  - fine tune $\mu H^\dagger H\phi$ term to zero

2HDM + scalar DM

- type II 2HDM + Z_2 odd singlet scalar S=DM

$$H_1 \sim (1,2,1/2)\ , \quad H_2 \sim (1,2,1/2)\ , \quad S \sim (1,1,0)$$

- DM directly couples to the Higgses

$$\mathcal{L} \supset \frac{\lambda_{S1}}{2} S^2 (H_1^\dagger H_1) + \frac{\lambda_{S2}}{2} S^2 (H_2^\dagger H_2)$$

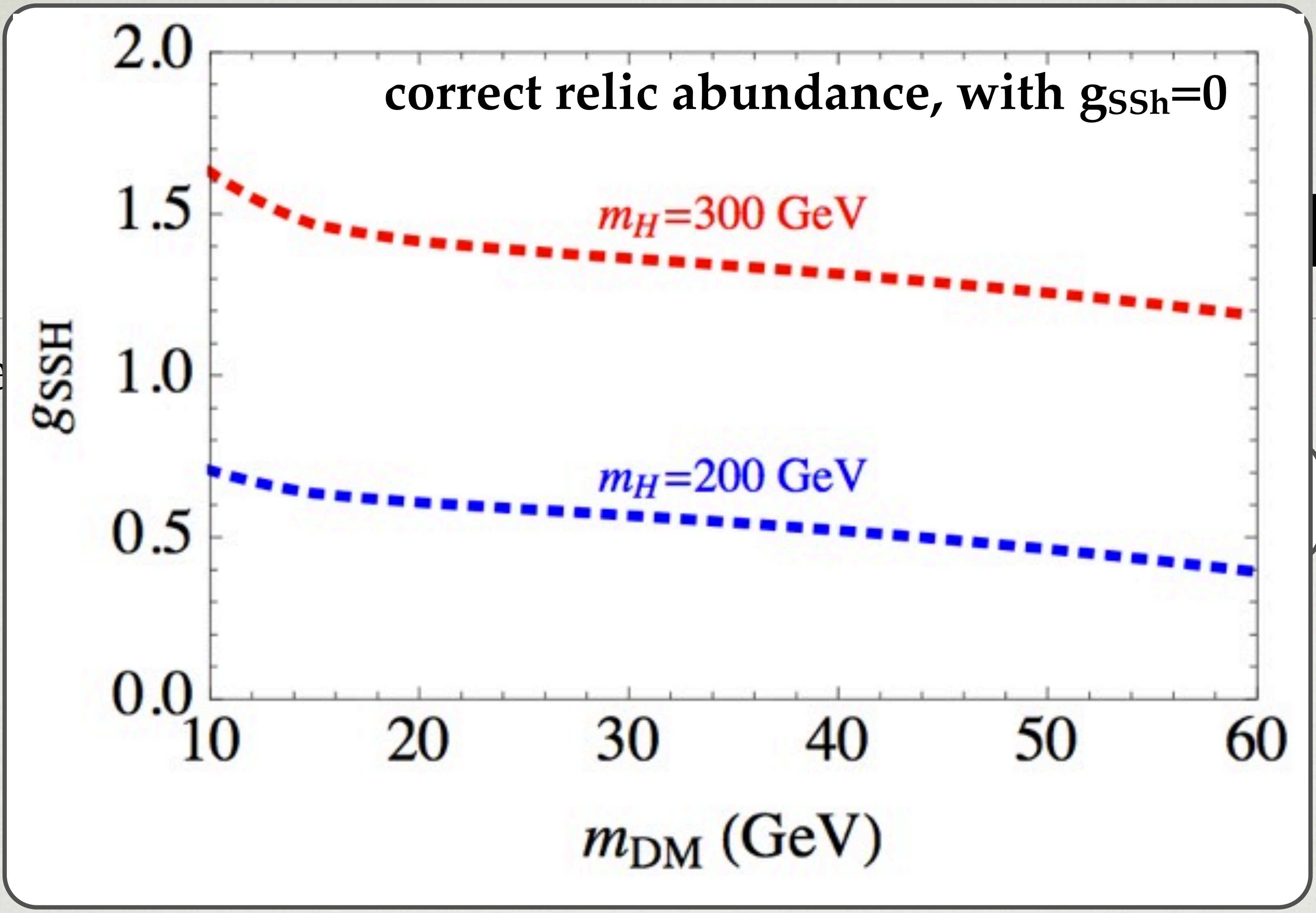
- DM annihilation through h and H

$$\sigma_{\rm ann} \propto (g_{SSh}/m_h^2 + g_{SSH}/m_H^2)^2$$

  - from $Br(h \to inv.)$ $g_{SSh} < 0.01$
  - correct relic abundance $g_{SSH} \sim O(1)$
  - enough freedom to arrange for this fine-tuned solution

$$\begin{aligned} g_{SSh} &= \lambda_{S1} \sin\alpha \cos\beta - \lambda_{S2} \cos\alpha \sin\beta, \\ g_{SSH} &= -\lambda_{S1} \cos\alpha \cos\beta - \lambda_{S2} \sin\alpha \sin\beta \end{aligned}$$

- type
- DM
- DM



$$\sigma_{\rm ann} \propto (g_{SSh}/m_h^2 + g_{SSH}/m_H^2)^2$$

- from *Br(h→inv.)* g_{SSh}<0.01
- correct relic abundance g_{SSH}~*O(1)*
- enough freedom to arrange for this fine-tuned solution

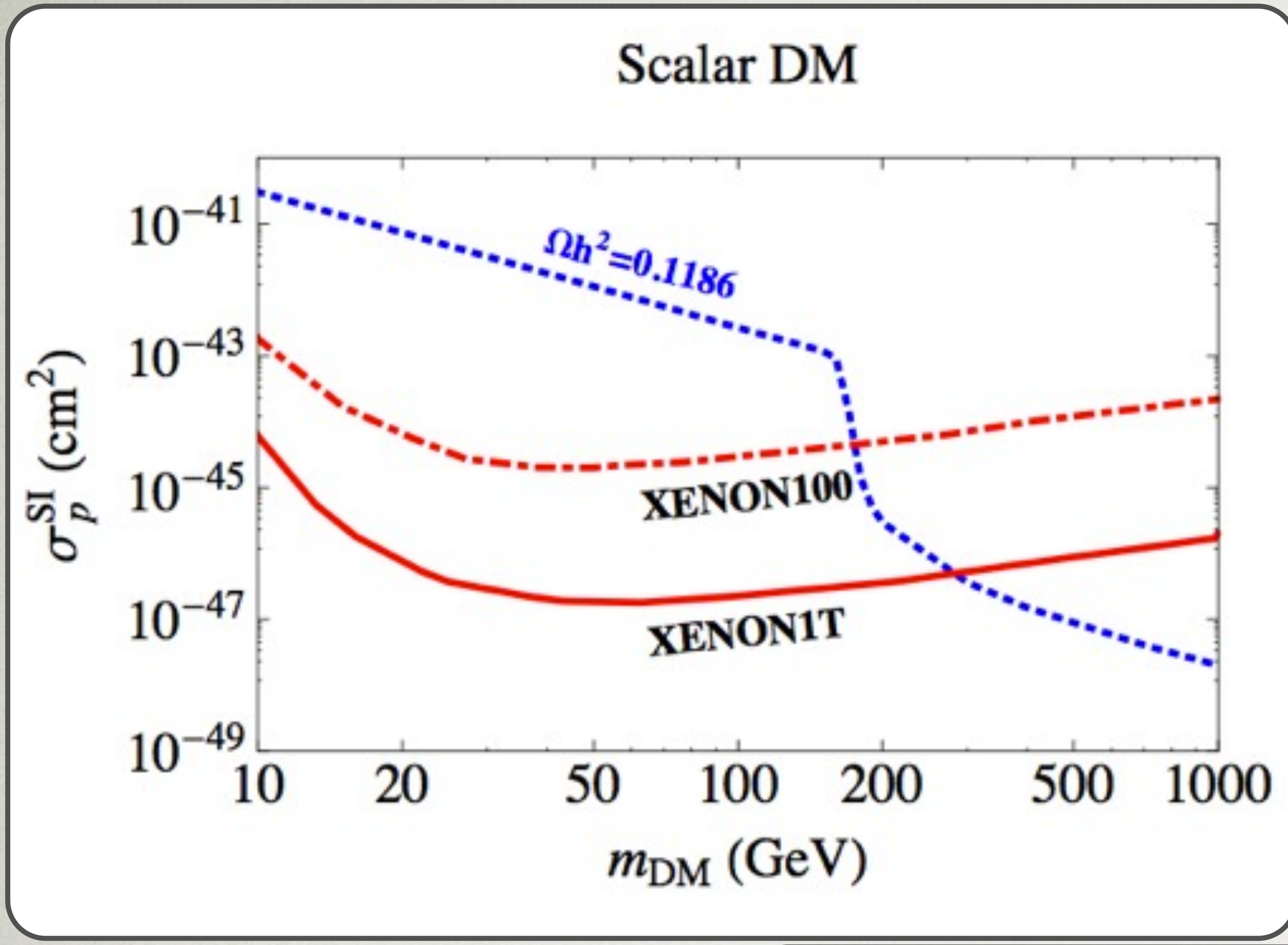
$$g_{SSh} = \lambda_{S1}\sin\alpha\cos\beta - \lambda_{S2}\cos\alpha\sin\beta,$$
$$g_{SSH} = -\lambda_{S1}\cos\alpha\cos\beta - \lambda_{S2}\sin\alpha\sin\beta,$$

DIRECT DETECTION BOUNDS

- direct detection also receives contributions from *h* and *H* exchanges
- can cancel the two for a particular choice of α and $\tan\beta$
  - e.g. to cancel the scattering on protons

$$\frac{\tan\alpha}{\tan\beta} = -\frac{f_d^p + f_s^p + f_b^p}{f_u^p + f_c^p + f_t^p}$$

  - for decoupling limit β-α=$\pi/2$ this requires $\tan\beta \simeq 0.6$
  - up to O(5%) this valid also for neutrons
  - enough to suppress direct DM bounds
  - note: unlike IVDM this cancellation valid also for light nuclei



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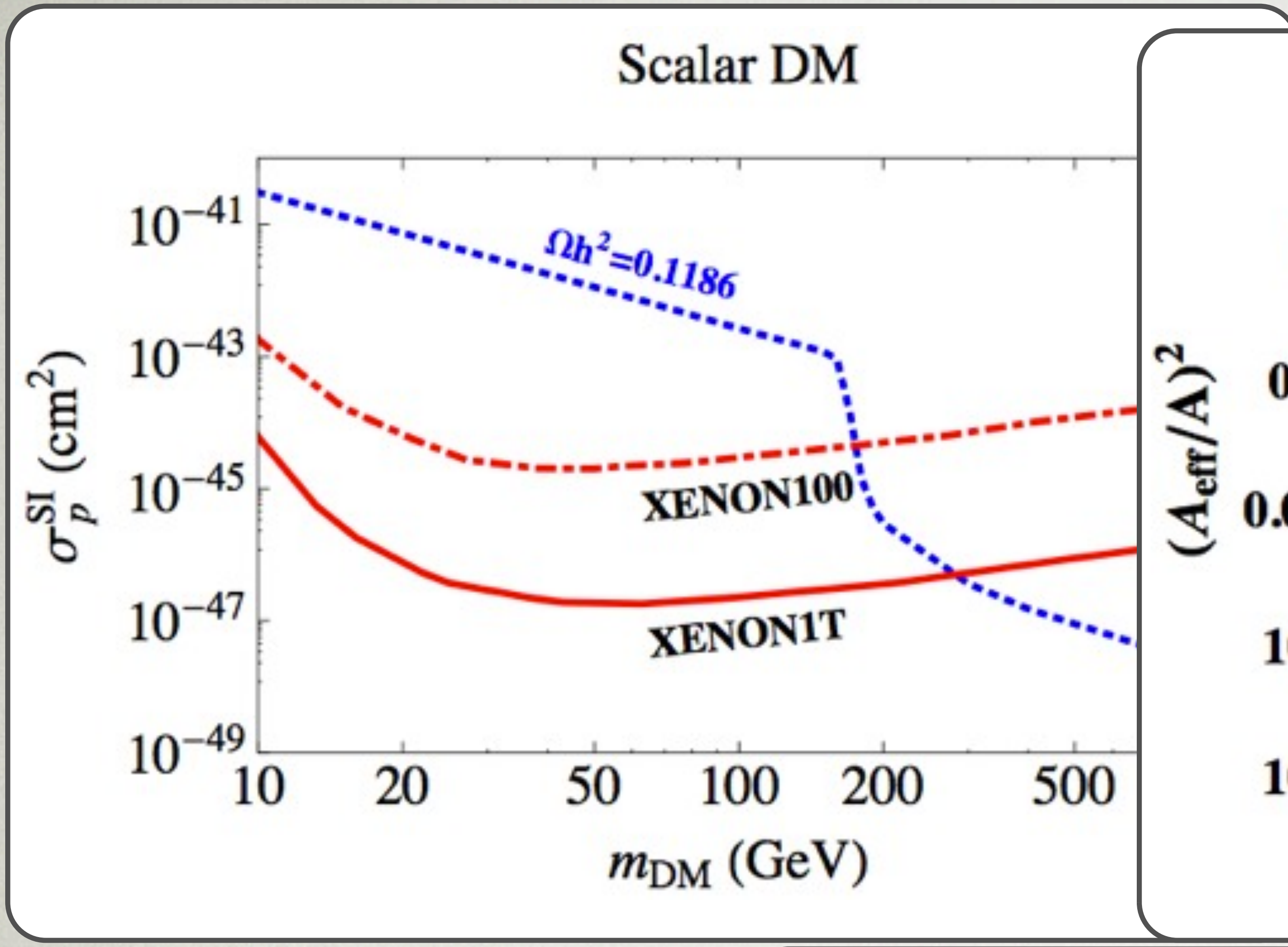

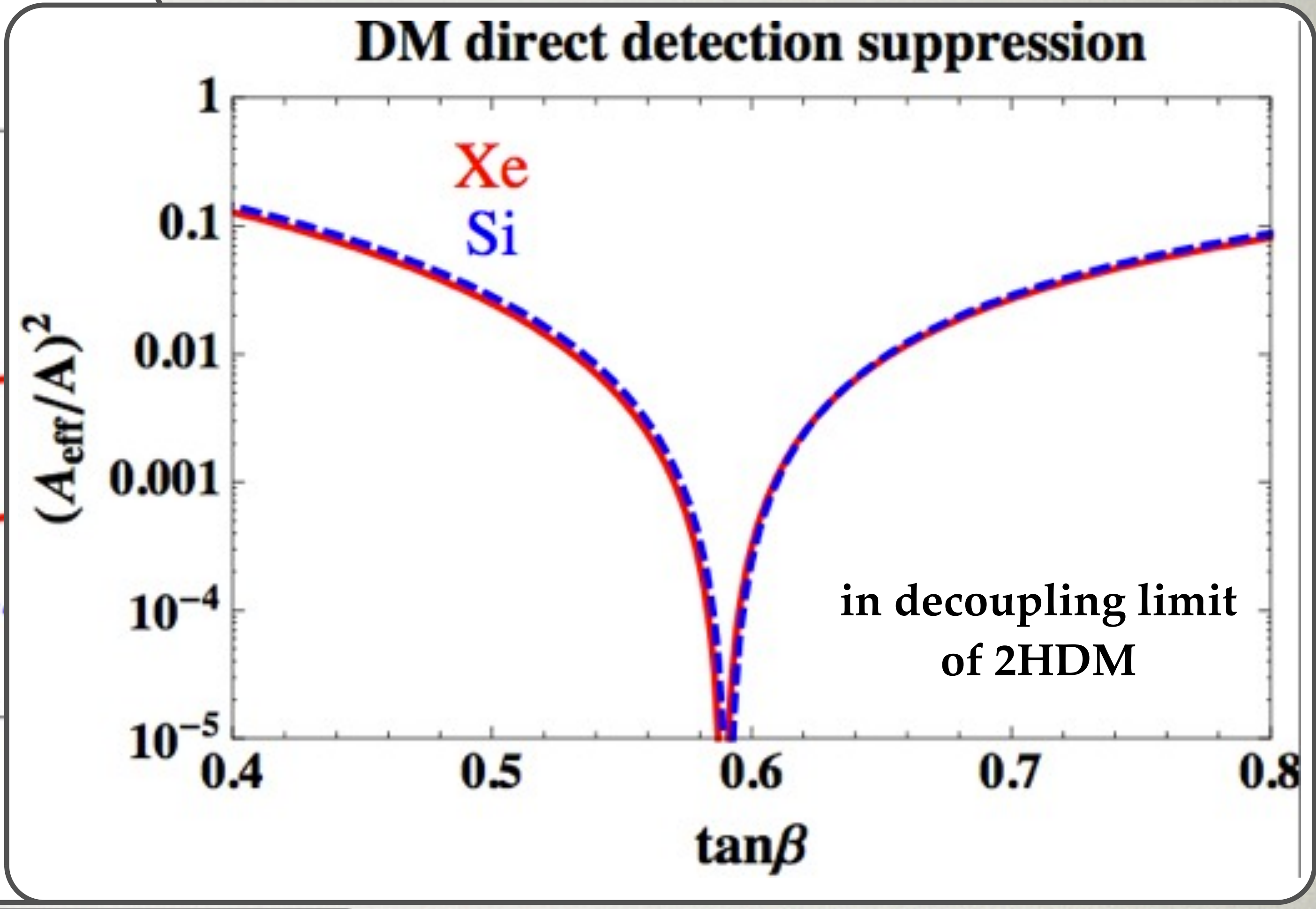

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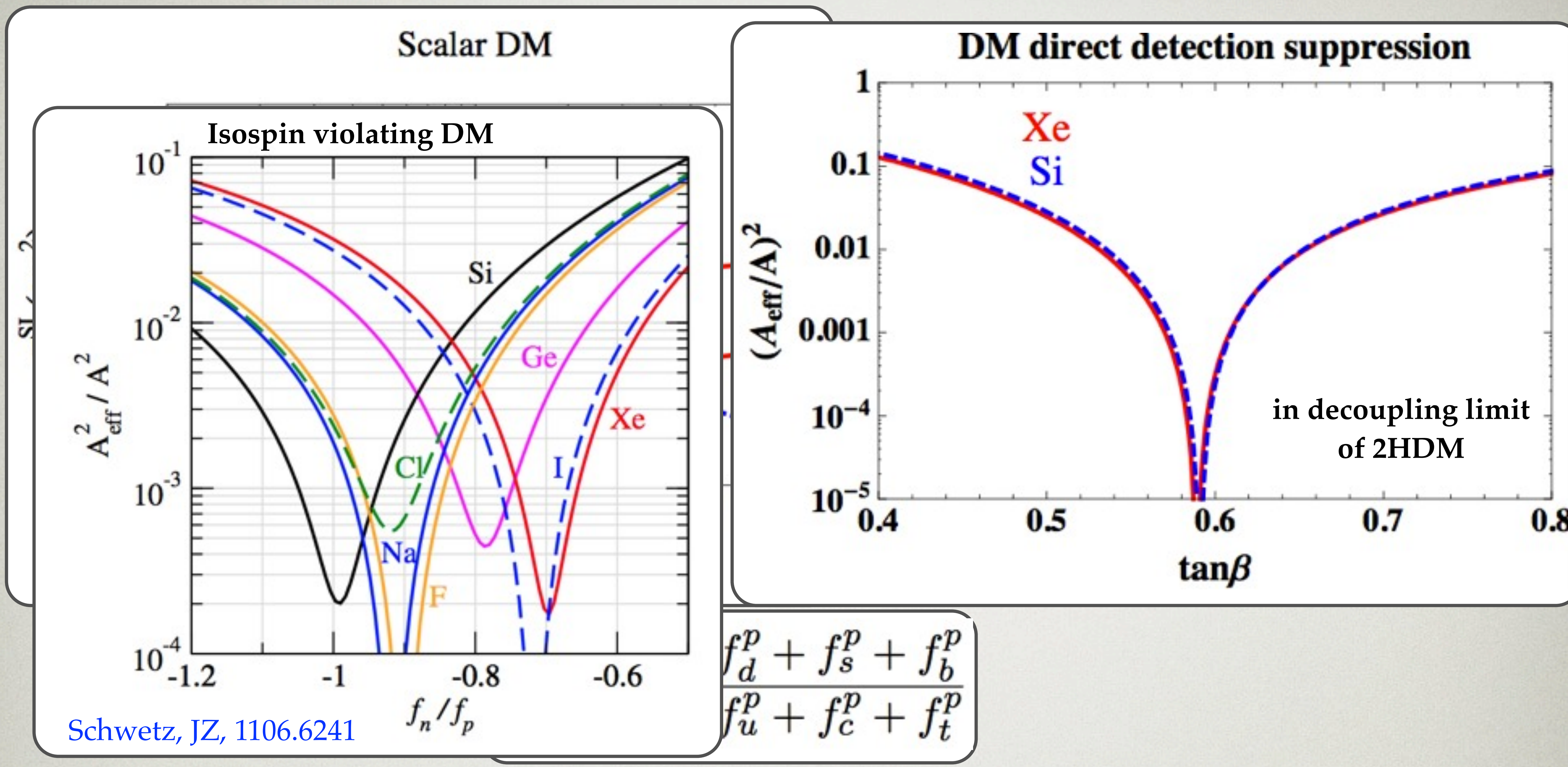

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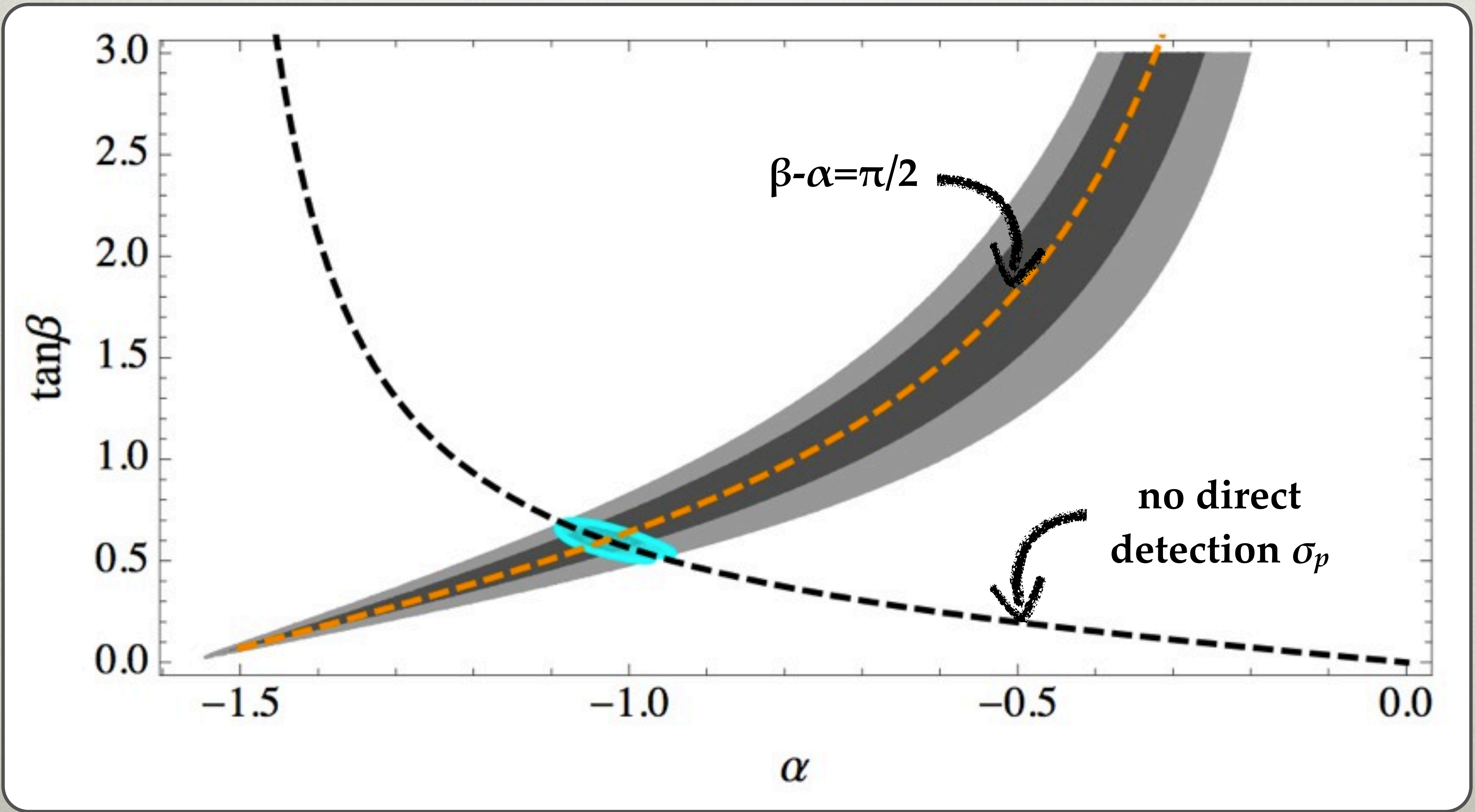
GLOBAL FITS WITH HIGGS DATA

- can perform the global fit with Higgs data and direct detection bounds



SEARCHING FOR THE HEAVY HIGGS

- to have the right relic density:heavy Higgs couples to DM
  - $\Rightarrow Br(H \rightarrow inv.) \simeq 100\%$
- perturbativity bounds $m_H \lesssim 850 GeV$ $(450 GeV)$ for $g_{SSH} \lesssim 4\pi$ (4)
- in decoupl. limit no HVV coupl., so $pp \rightarrow Zh \rightarrow l+l-inv.$ does not apply
- dominant production at LHC $gg \rightarrow H(t\bar{t})$
  - for $t\bar{t}+MET$ and $m_H = 200, 300$ GeV xsec is $\sigma= 29fb, 7.7fb$ $(LHC8)$ and $\sigma= 150$ fb, 51 fb $(LHC14)$
  - for $gg \rightarrow H+jet$ predicts $\sigma(gg \rightarrow Hj) \times B(H \rightarrow inv)/\sigma_{SM}=2.7$

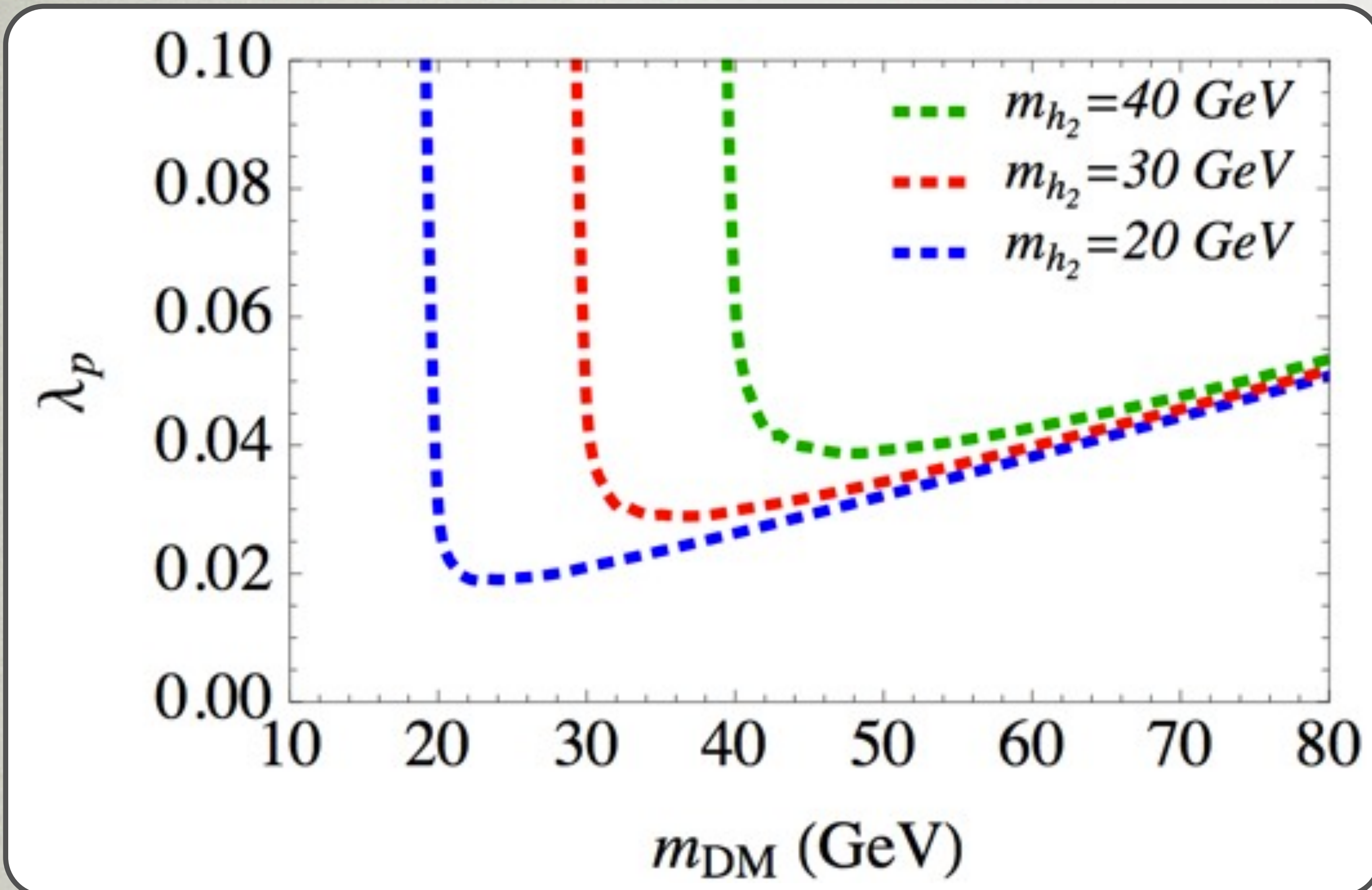
SM+DM+extra scalar

- add to the SM two real scalars, ϕ and S(=DM, Z_2-odd)

$$\phi \sim (1,1,0)\,, \quad S \sim (1,1,0)$$

- mass eigenstates
$$\begin{aligned} h_1 &= h\cos\alpha + \phi\sin\alpha\,, \\ h_2 &= -h\sin\alpha + \phi\cos\alpha\,, \end{aligned}$$

- α constrained by LEP, $|sin\alpha| < 0.13(0.2)$ for $m_{h2} = 20(50)GeV$
- in the Lagr.: $$V \supset \frac{\lambda_5}{2} H^\dagger H S^2 + \frac{\lambda_6}{2}\phi^2 S^2$$
  - relic abundance from $SS \to h_2 h_2$, governed by
  $$\lambda_p = \lambda_6 \cos^2\alpha + \lambda_5 \sin^2\alpha$$
  - $Br(h \to inv.)$ governed by
  $$\lambda_h = \lambda_5 \cos\alpha - \lambda_6 \sin\alpha$$
- also additional h decay channels from $h_1 \to h_2 h_2$, $h_2 \to \bar{b} b$



RA SCALAR

$S(=DM, Z_2\text{-odd})$

$(1, 1, 0)$

$\sin\alpha\,,$

$\phi\cos\alpha\,,$

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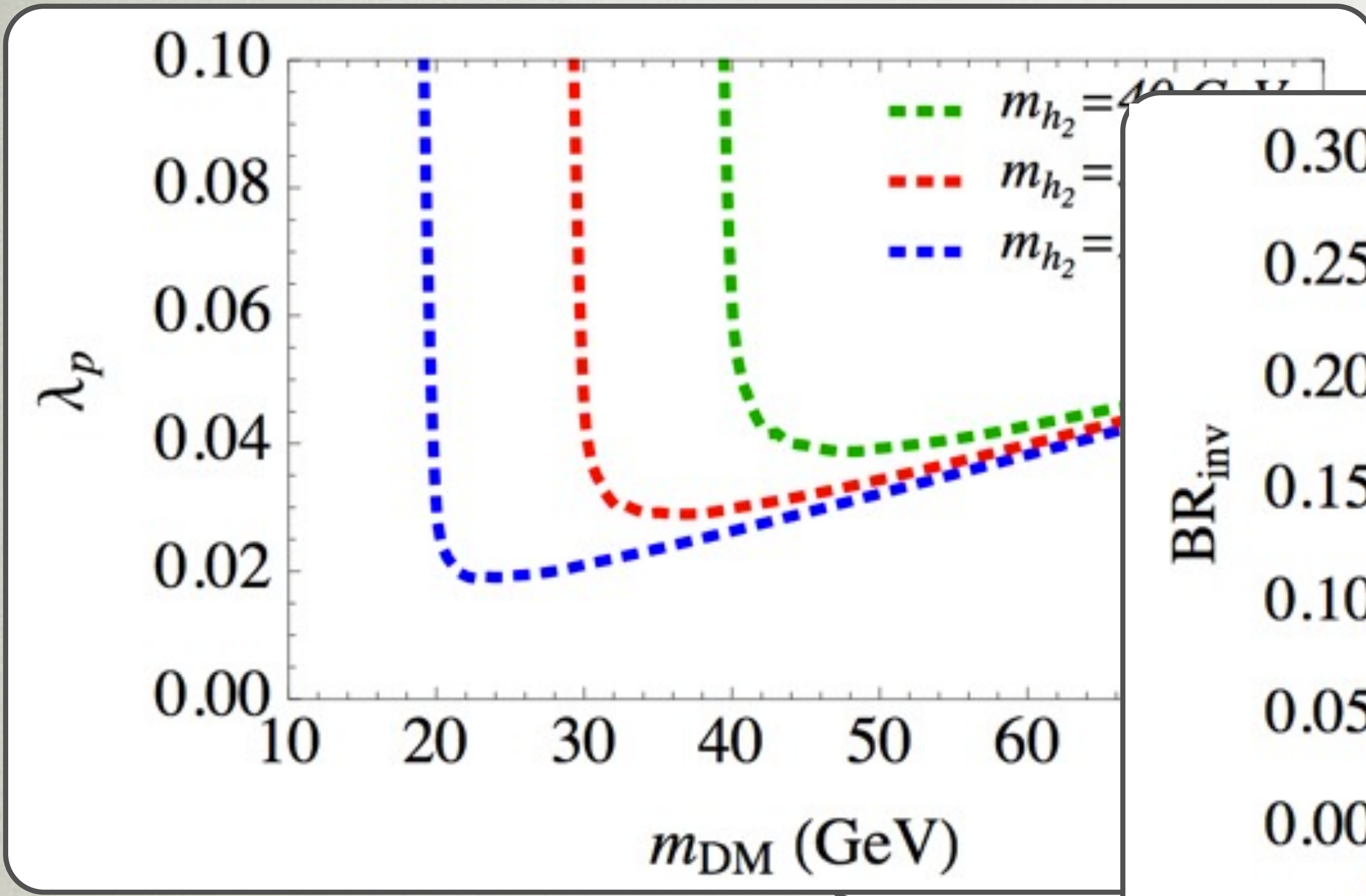

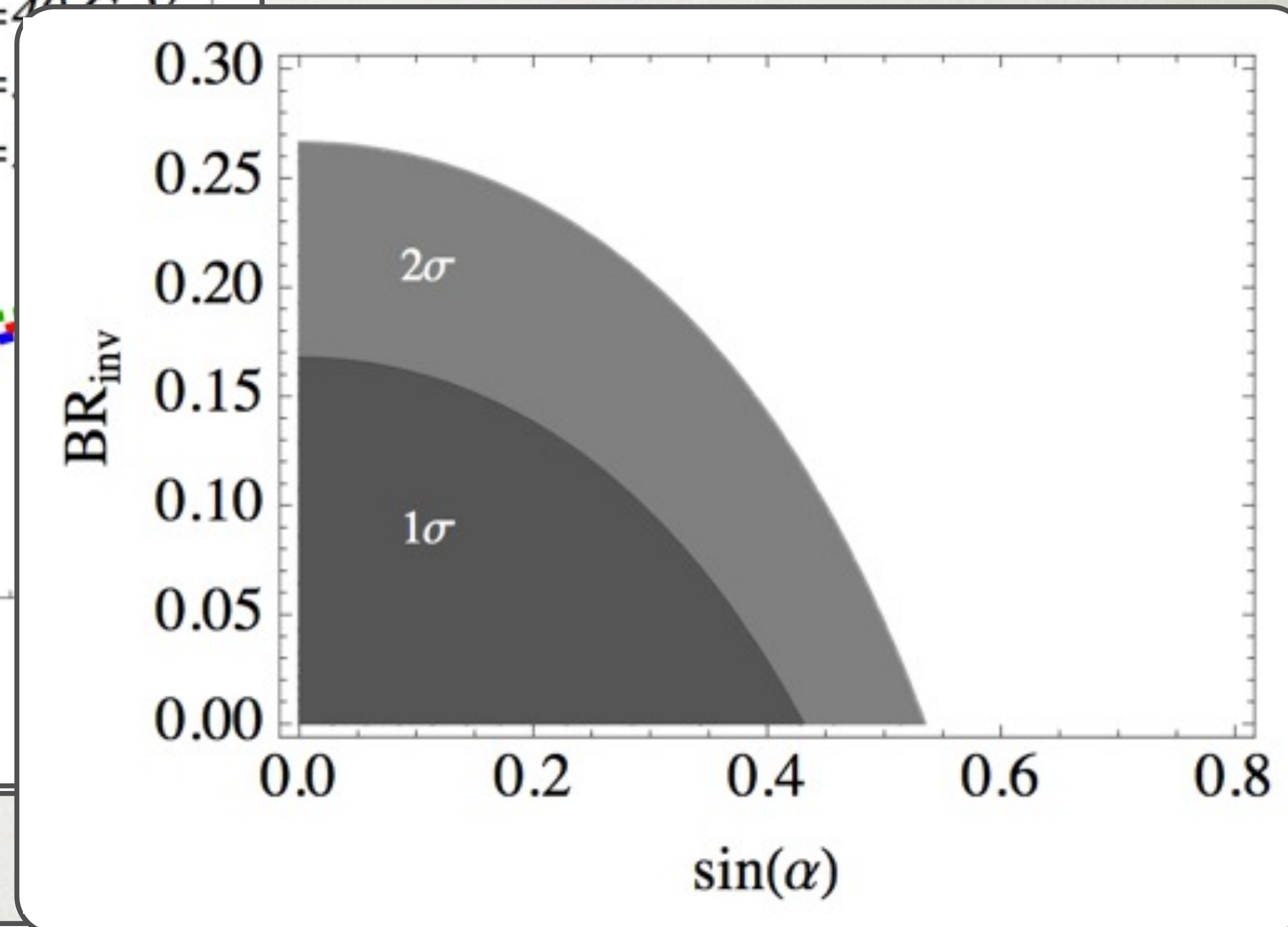

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RECAPITULATE

- viable Higgs portals:
  - require extra light states
  - may need fine-tuning to avoid bounds
    - though not always (SM+DM +singlet)

MODIFYING FLAVOR STRUCTURE

Eby, Uttarayat, Wijewardhana, JZ, work in progress

- another interesting possibility is to modify the flavor structure
- if the Higgs couplings to fermions are not the SM ones
  - e.g. changing $hb\bar{b}$
  - bounds on $h \to inv.$ tight enough that the min. Higgs portal still excluded
  - crucial $Z(h \to inv.)$ associated production
- flavor violating Higgs couplings
  - from mixing tightly constrained, so $b \to s+MET$, $s \to d+MET$ bounds saturated for O(10) DM-Higgs couplings

    Kamenik, Smith, 1111.6402
  - for (minimal) Higgs portal thus FV irrelevant
  - FCNCs could be important if other mediators or more complicated DM sector

Nelson, Scholtz, 1311.0040

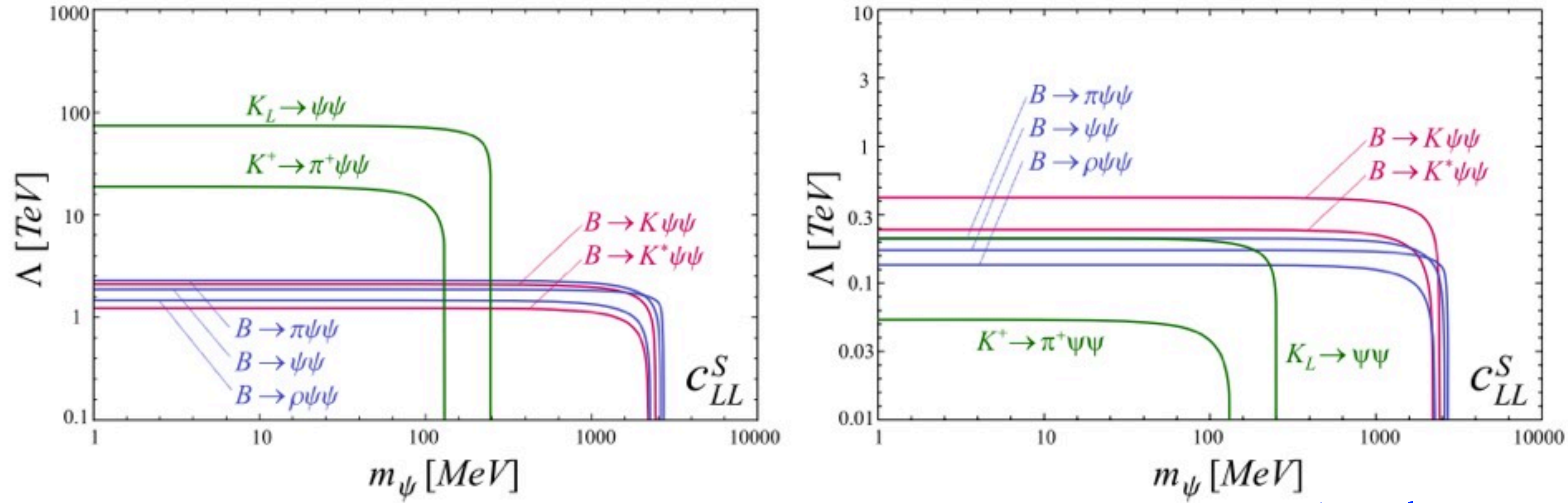
…na, JZ, work in progress

Technique	Coupling	Constraint
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2,\ \lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2,\ \lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2,\ \lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2),\ \mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2),\ \mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$
single-top production [49]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 3.7
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 1.6
$t \to hj$ [50]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.34
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.34
D^0 oscillations [48]	$\lvert Y_{ut}Y_{ct}\rvert,\ \lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$
	$\lvert Y_{tu}Y_{ct}\rvert,\ \lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$
neutron EDM [37]	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$

Harnik, Kopp, JZ, 1209.1397

…menik, Smith, 1111.6402

…z, 1311.0040



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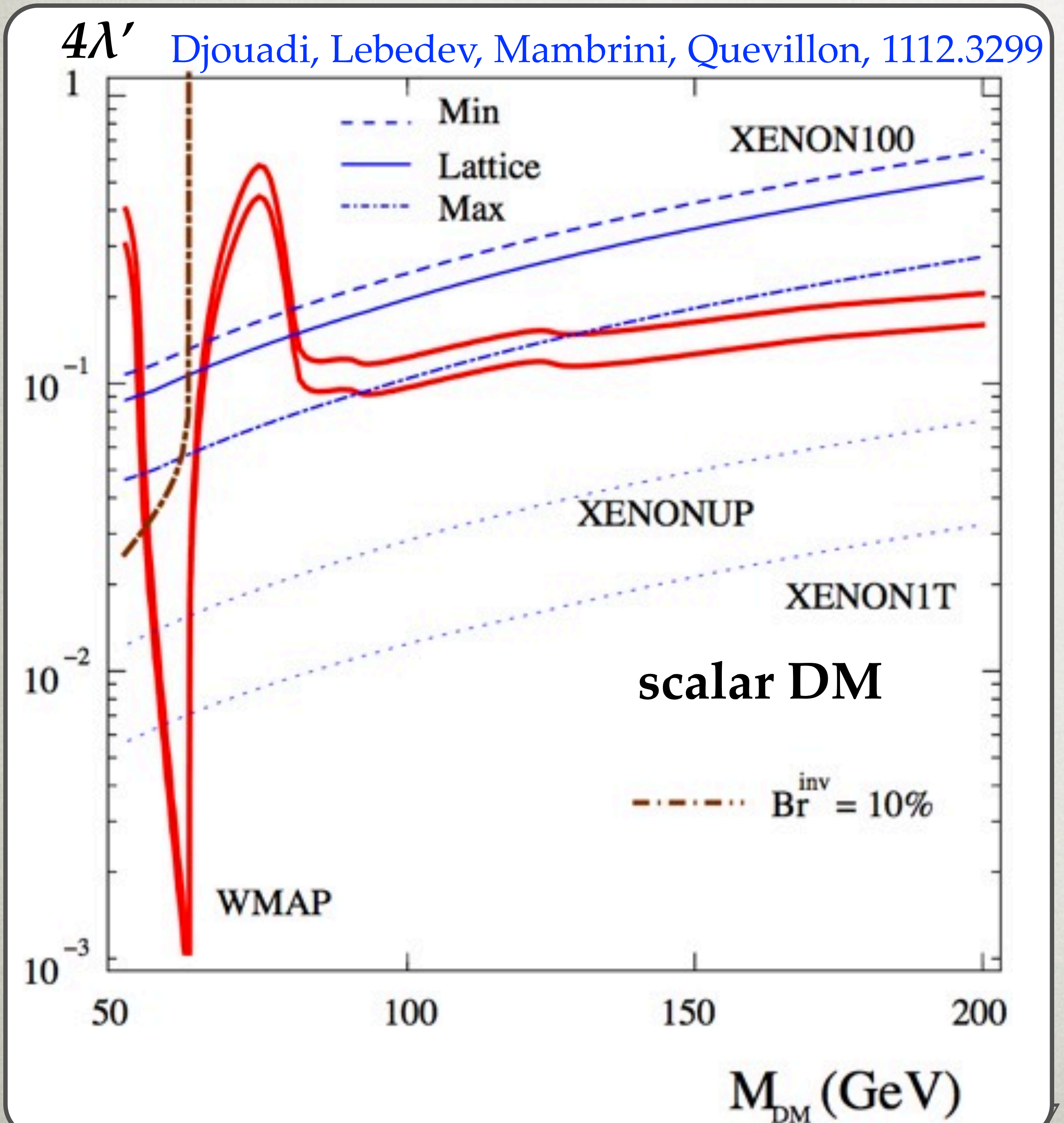
Nelson, Scholtz, 1311.0040

HEAVY DM AND HIGGS PORTAL

HEAVY DM AND MINIMAL HIGGS PORTAL

- minimal Higgs portal for heavy DM ($m_{DM} \lesssim m_h/2$)



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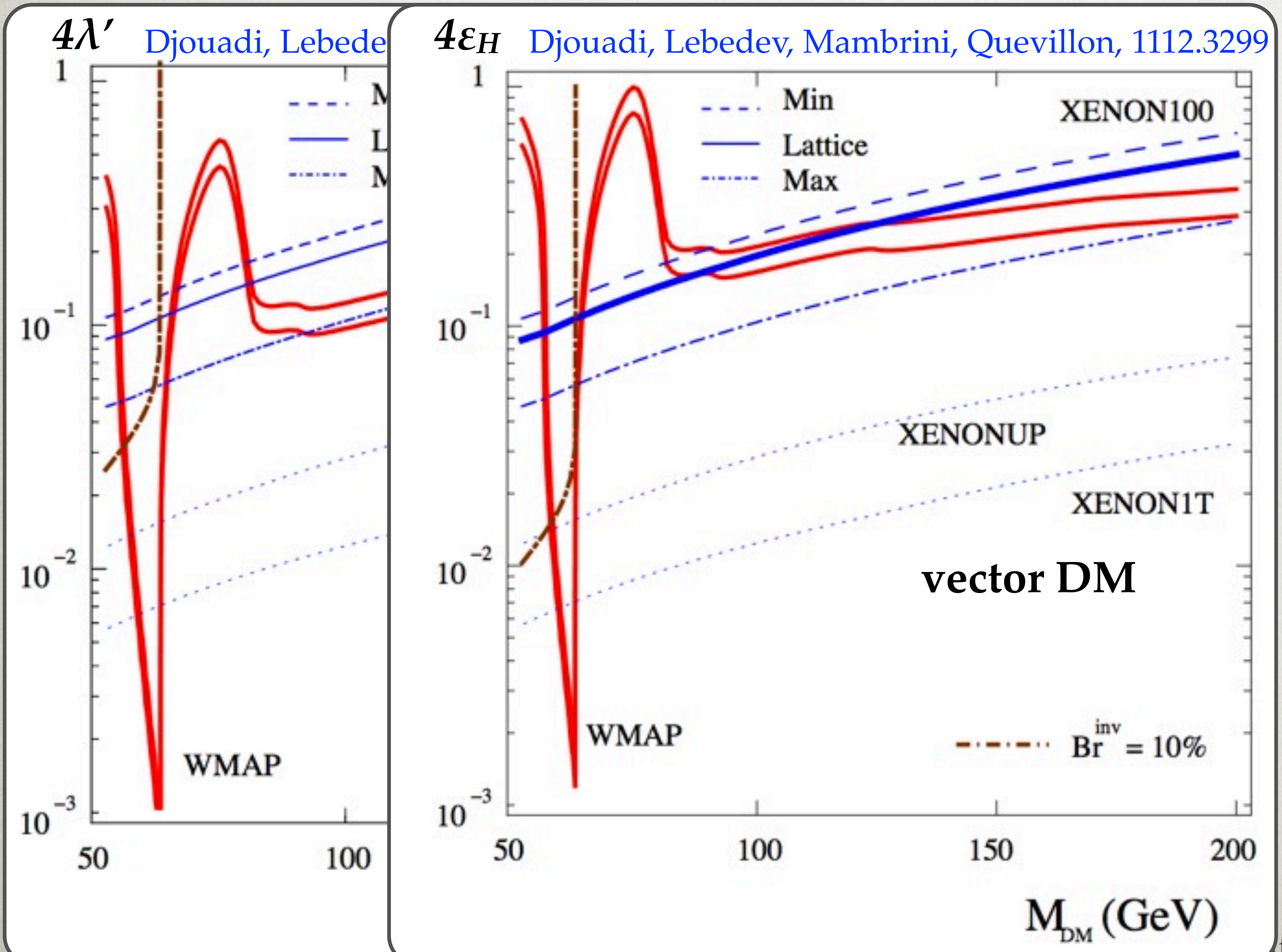

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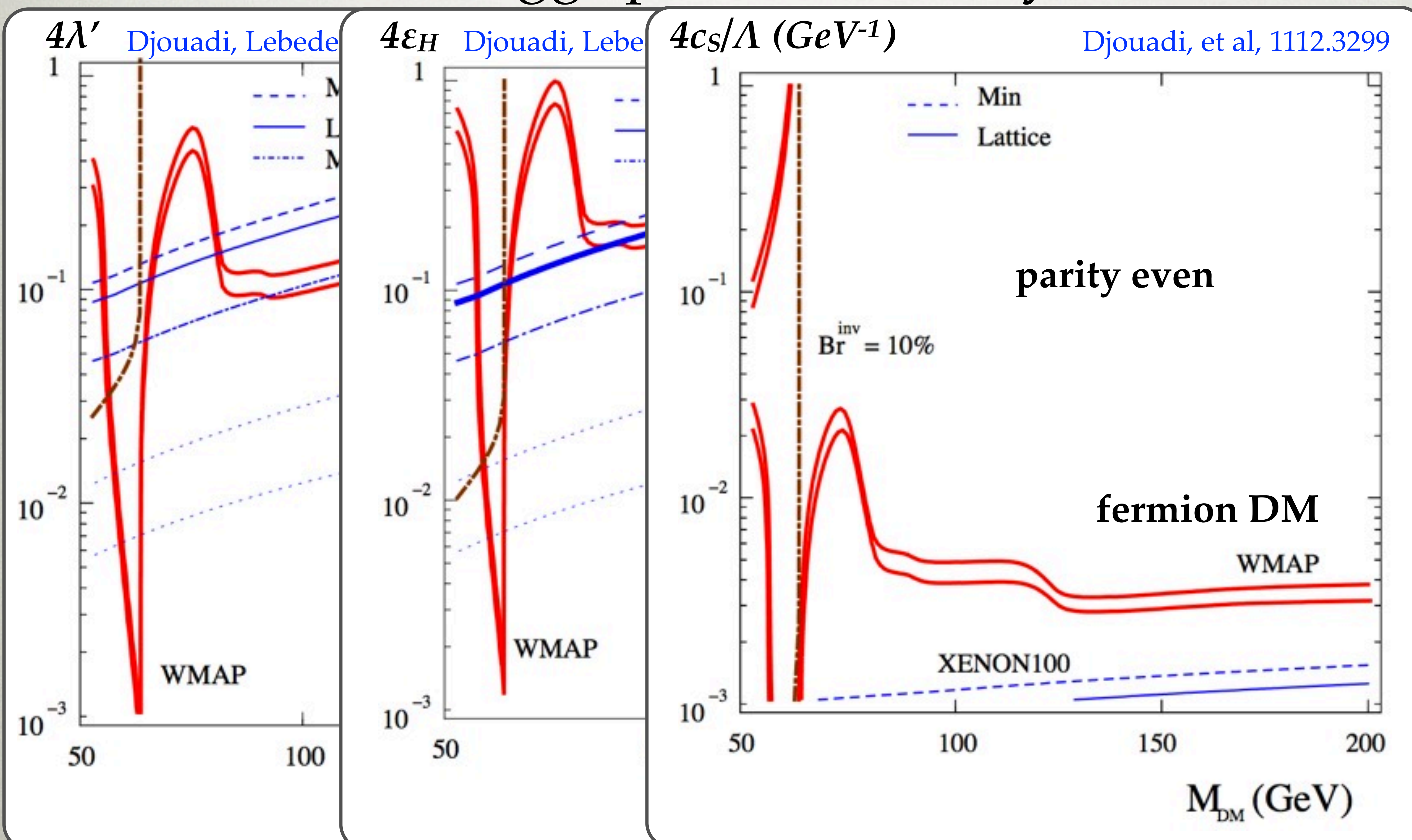


HEAVY DM HIGGS PORTAL

Lopez-Honorez, Schwetz, JZ, 1203.2064

- invisible higgs decay bounds no longer relevant
- at present direct detection relevant only for fermionic DM
- the limits depend on the relative size of parity even and parity odd operators

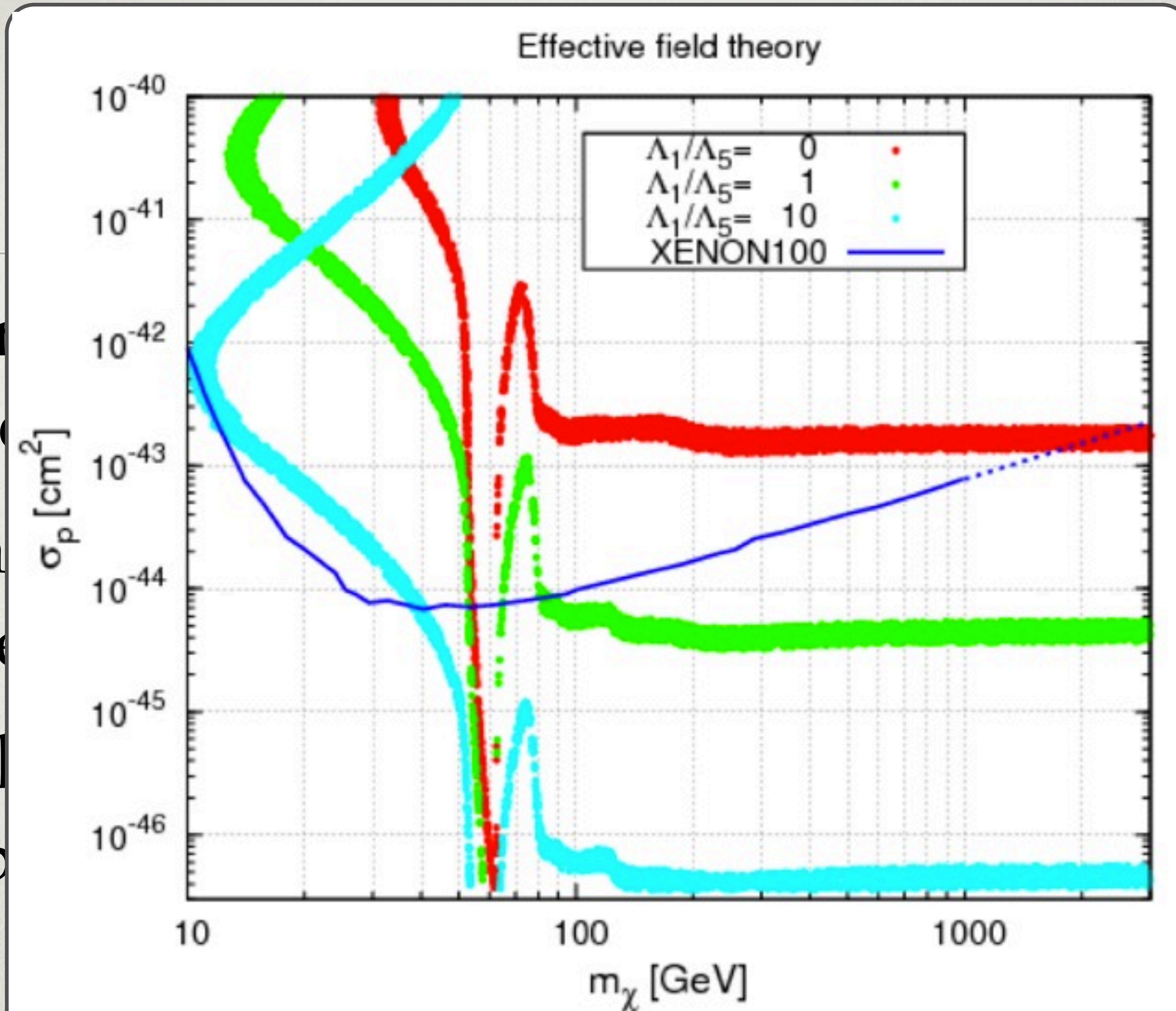
$$H_{\rm eff} = \frac{1}{\Lambda_1} Q_1 + \frac{1}{\Lambda_5} Q_5$$

$$Q_1 = (H^\dagger H)(\bar{\chi}\chi)\,, \qquad Q_5 = i(H^\dagger H)(\bar{\chi}\gamma_5\chi)\,,$$

H … L

Schwetz, JZ, 1203.2064

- i… r
  r…
- a… y for
  f…
- t… f
  p…



Lopez-Honorez, Schwetz, JZ, 1203.2064

$$Q_1 = (H^\dagger H)(\bar\chi\chi)\,, \qquad Q_5 = i(H^\dagger H)(\bar\chi\gamma_5\chi)\,,$$

see also Pospelov, Ritz, 1109.4872

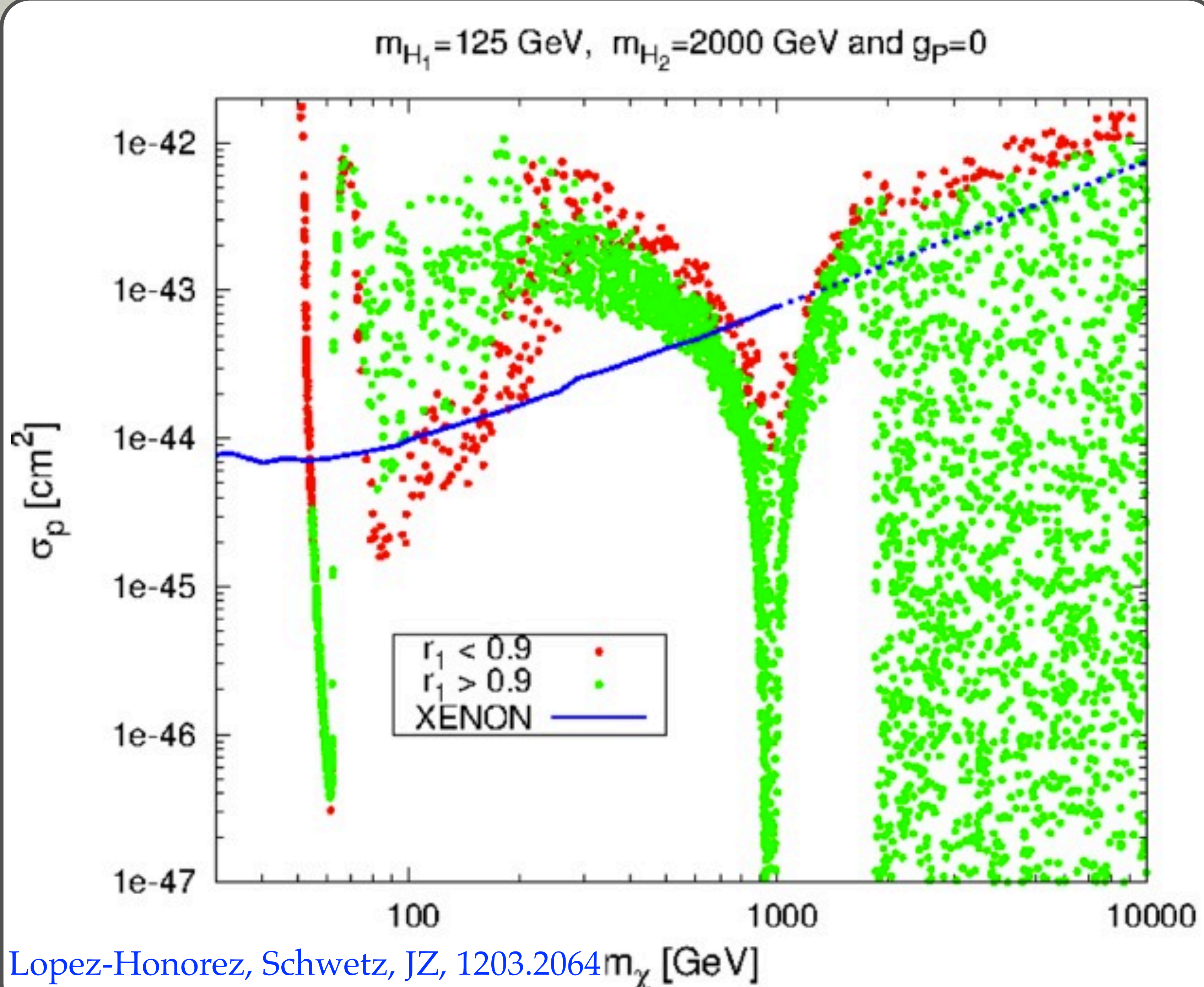
PARITY EVEN HIGGS PORTAL

- for minimal parity even fermionic Higgs portal
  - DM needs to be heavier than ~2TeV
- assumes EFT valid
- invalidate EFT and one can still have parity even fermionic Higgs portal
- illustrate this in SM+Majorana χ+scalar singlet
  - resonant Higgs portal $\chi\chi \to H_2 \to SM+SM$
  - indirect Higgs portal $\chi\chi \to H_2H_2,\ H_2H_2 \to SM+SM$

$$r_i \equiv \frac{\sigma_{H_i} \mathrm{Br}_{H_i \to X}}{\sigma_{H_i}^{\mathrm{SM}} \mathrm{Br}_{H_i \to X}^{\mathrm{SM}}}$$

$$r_1 = \cos^4\alpha \, \frac{\Gamma_{H_1}^{\mathrm{SM}}}{\Gamma_{H_1}} \quad \text{and} \quad r_2 = \sin^4\alpha \, \frac{\Gamma_{H_2}^{\mathrm{SM}}}{\Gamma_{H_2}}$$

see also Pospelov, Ritz, 1109.4872



Lopez-Honorez, Schwetz, JZ, 1203.2064

PORTAL

iggs portal

V

parity even

lar singlet

M+SM

- indirect Higgs portal $\chi\chi \to H_2H_2$, $H_2H_2 \to SM+SM$

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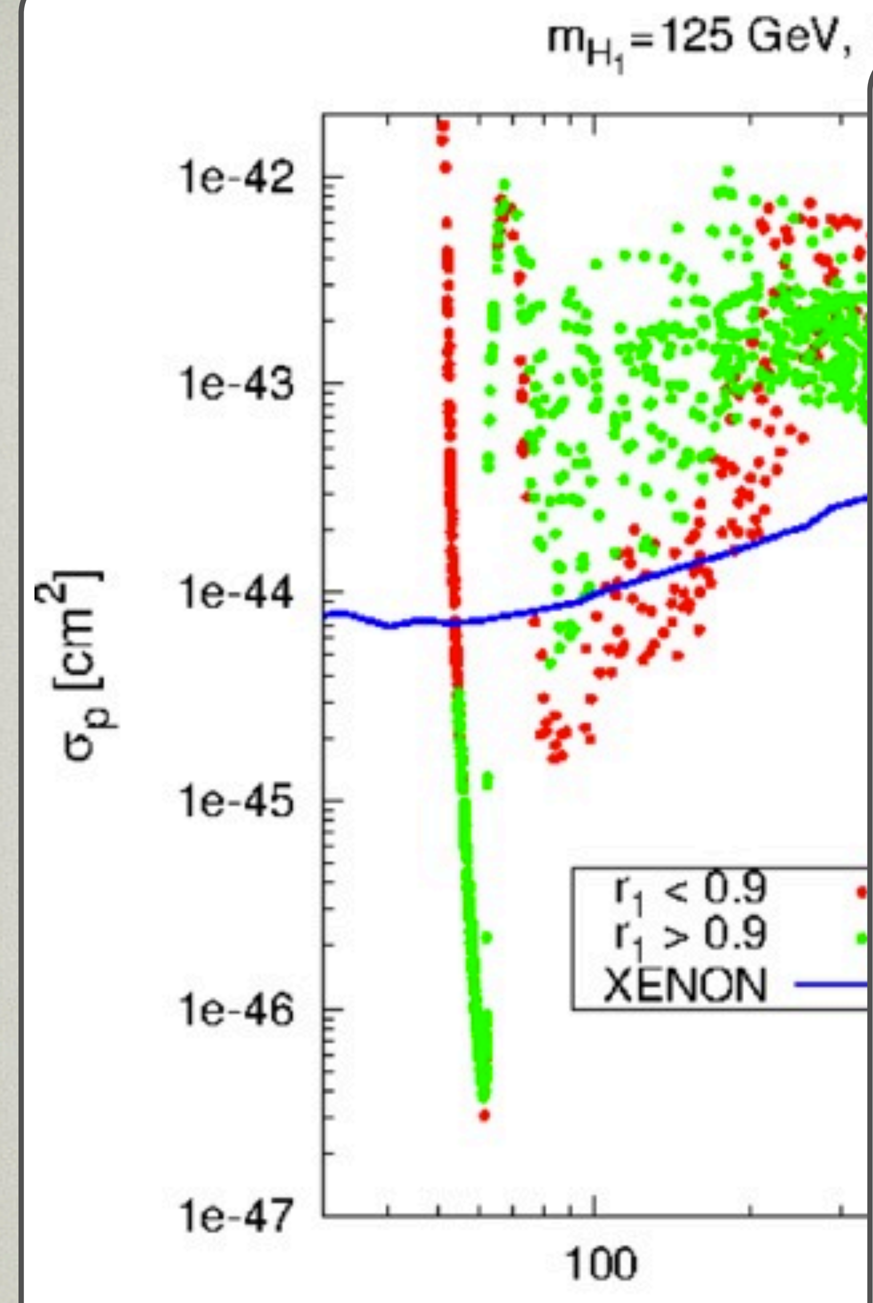
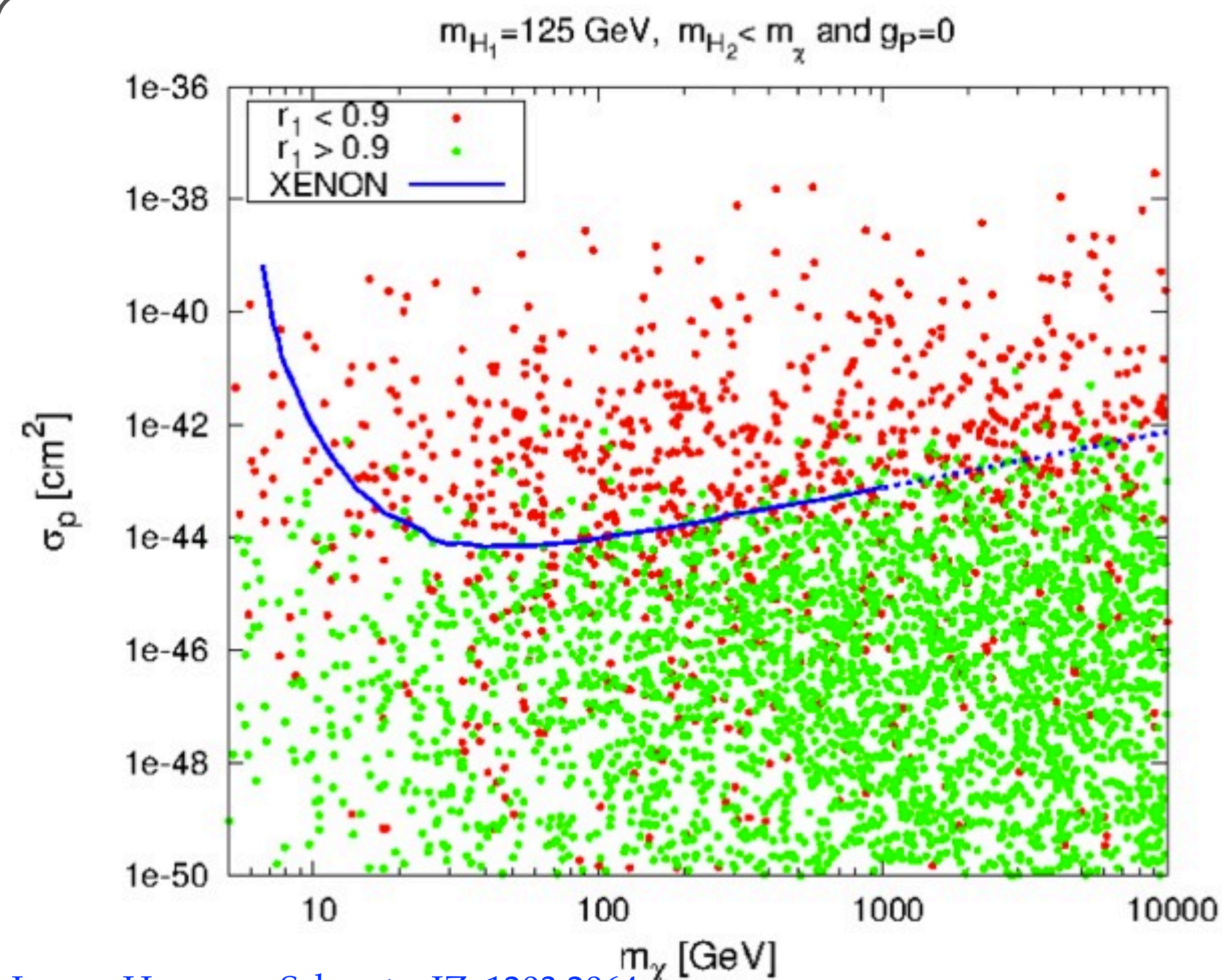


Lopez-Honorez, Schwetz, JZ, 1203.2064



Lopez-Honorez, Schwetz, JZ, 1203.2064

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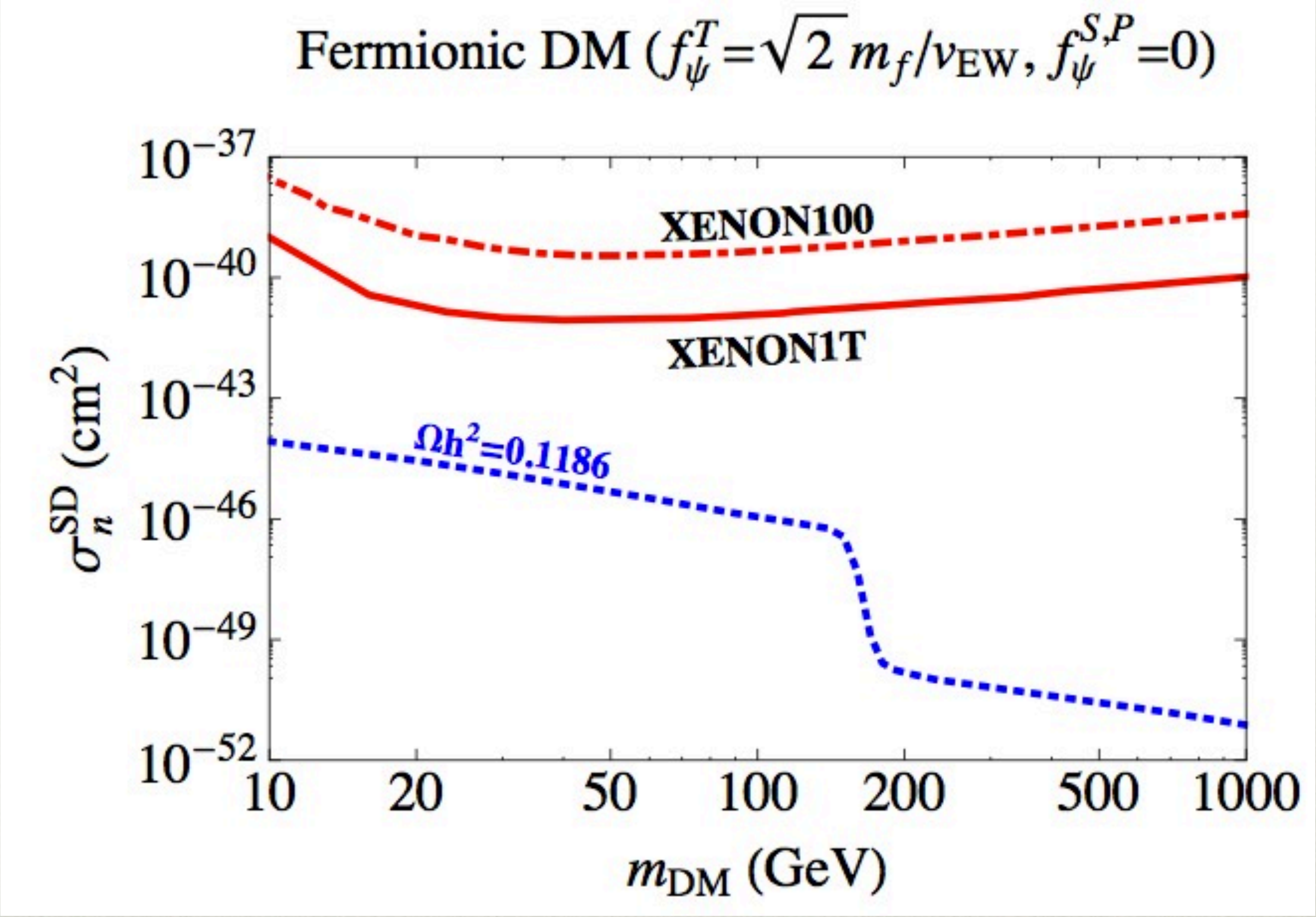
$$r_1 = \cos^4\alpha\, \frac{\Gamma^{\mathrm{SM}}_{H_1}}{\Gamma_{H_1}} \quad \text{and} \quad r_2 = \sin^4\alpha\, \frac{\Gamma^{\mathrm{SM}}_{H_2}}{\Gamma_{H_2}}$$

CONCLUSIONS

- viable Higgs portals with light DM excluded require other light states
- for heavy fermionic DM Higgs portal several ways to evade bounds on parity even case

BACKUP SLIDES



Fermionic DM ($f_\psi^T = \sqrt{2}\, m_f / v_{EW}$, $f_\psi^{S,P} = 0$)
XENON100
XENON1T
$\Omega h^2 = 0.1186$
σ_n^{SD} (cm^2)
m_{DM} (GeV)
10^{-37}
10^{-40}
10^{-43}
10^{-46}
10^{-49}
10^{-52}
10
20
50
100
200
500
1000

NEW STATES

- the new states
  - $\phi - \Delta^0$ mixed states, with masses $m_{1,2}$
  - Δ^+ or Δ^{++} particles
- have masses *O(100)* GeV for light DM (depending on couplings)
- can have other phenomenological consequences
  - e.g. in a flavor model could lead to FCNCs
  - $l_a \to l_b\gamma$ and $l^-{}_a \to l^+{}_b\, l^-{}_c\, l^-{}_d$