Phenomenology of Spontaneously Broken Dark Matter Hidden Sector

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COSMO/CosPA 2010

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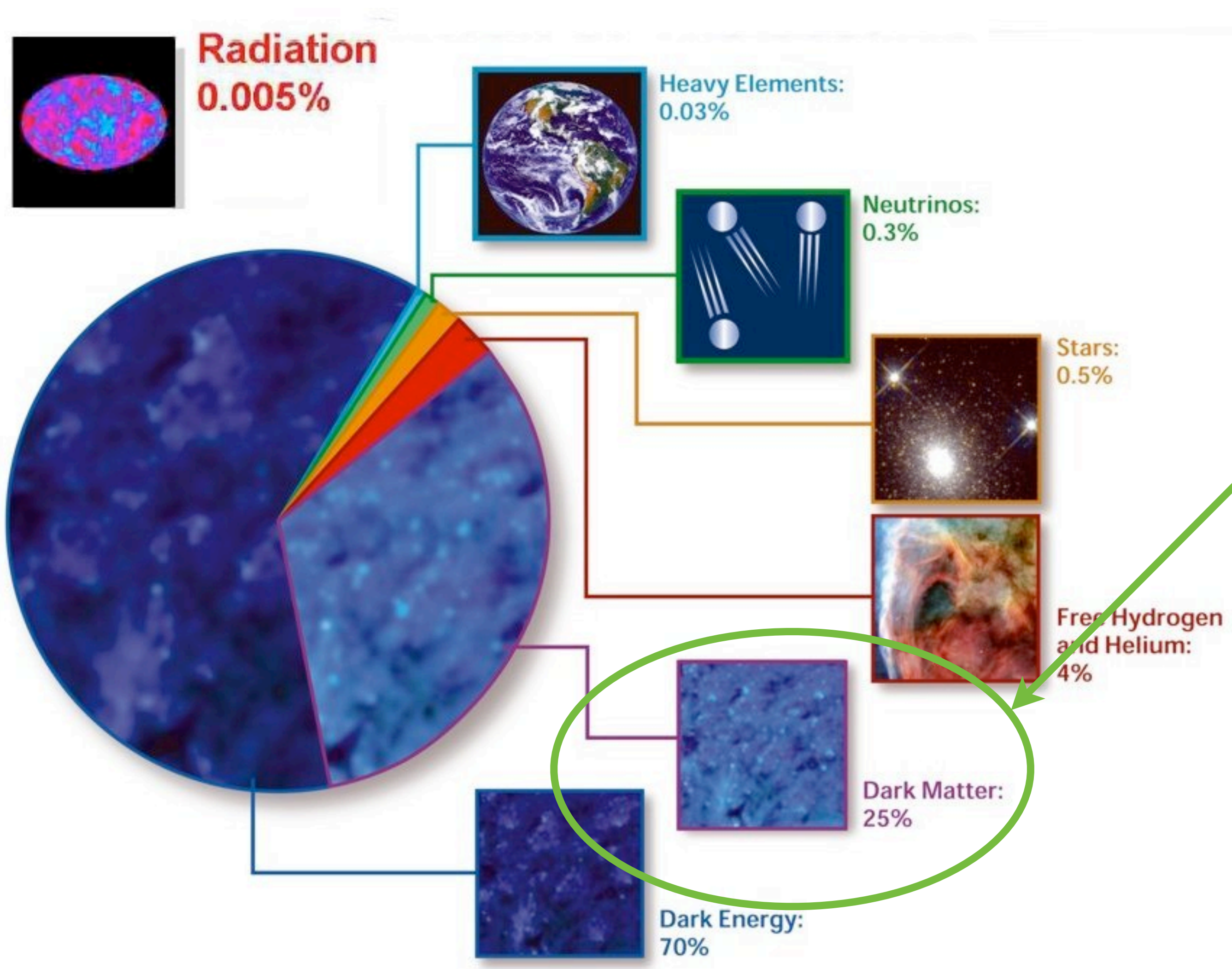
The Dark Universe



Dark Matter (DM)

Only gravitational evidence

Properties:

- Non Baryonic, neutral
- Weakly interacting
- Cold: Slow moving (or warm)
- Extremely long lived

$$\tau_{DM} > \tau_U \sim 10^{18}\,\text{sec}$$

but not necessarily stable

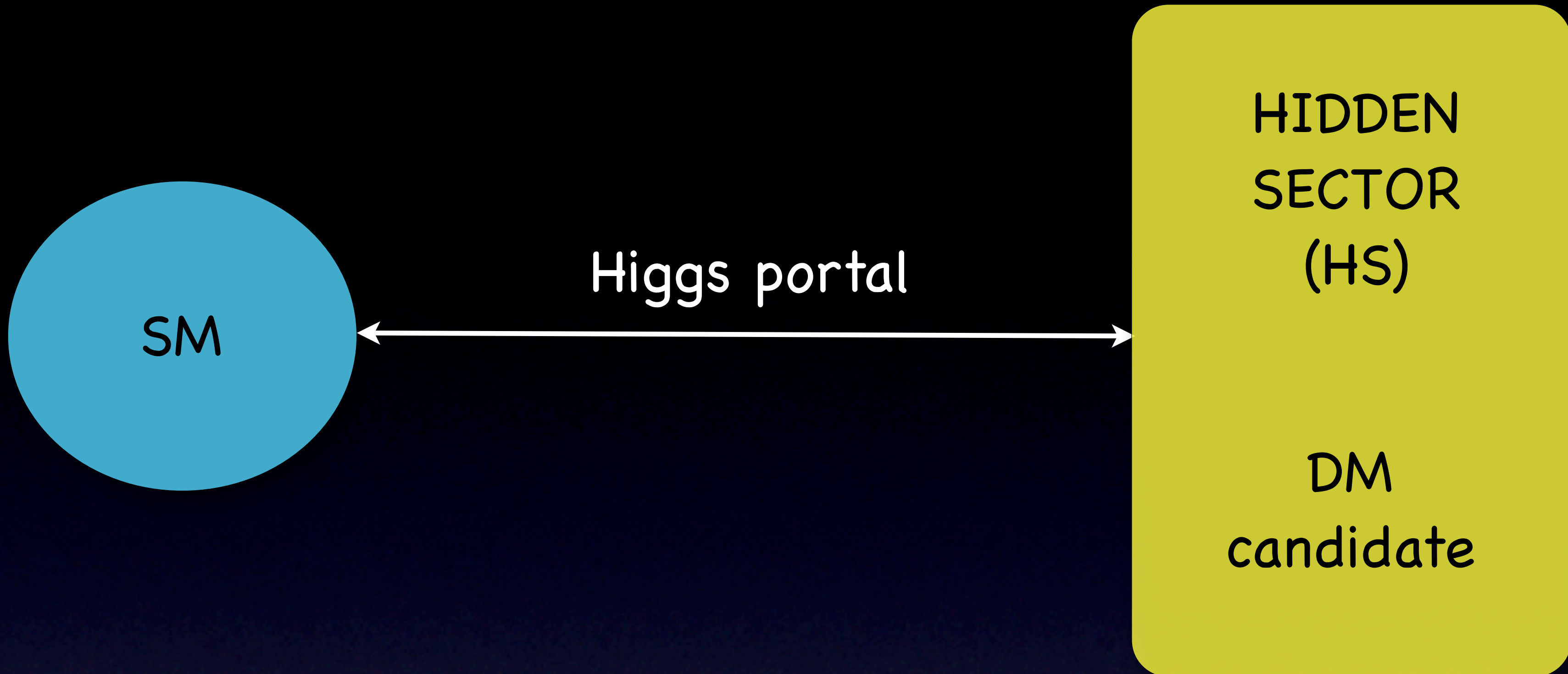
Independent (non-gravitational) evidences needed to determine the nature of the DM

Direct detection, Colliders and Indirect searches

evidence of a primary positron component (possibly accompanied by electrons) from PAMELA (Nature 458, 2009), ATIC (arXiv:0905.0105) and FERMI (PRL 102,2009)

Focus on DM models that may account for the positron component

$$\mathcal{L} = \mathcal{L}_{\rm HS} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm Higgs\ portal}$$

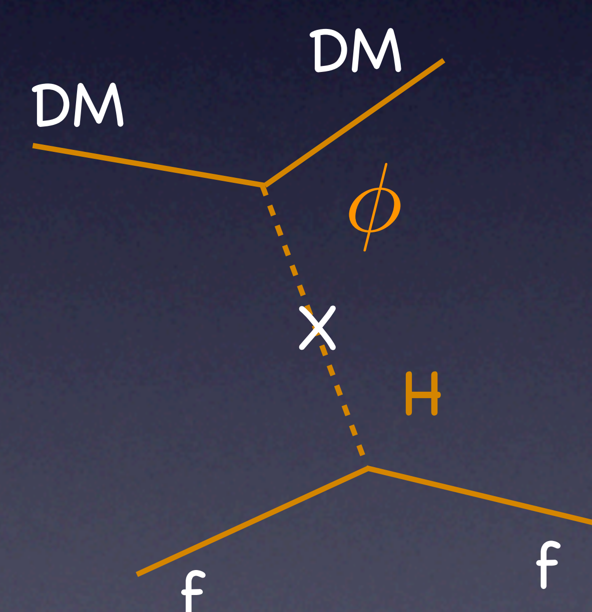


Pospelov, Ritz and Voloshin '07
Arkani-Hamed, Finkbeiner, Slatyer and Weiner '08
Hambye '08, Chen, Cline and Frey '09

The DM sector is gauged under an abelian or non-abelian group

$$\mathcal{L}_{\rm HS} \supset -\mu_\phi^2 \phi^\dagger \phi - \lambda_\phi (\phi^\dagger \phi)^2$$

$$\mathcal{L}_{\rm Higgs\ portal} \supset \ -\lambda_{\rm Hp} \phi^\dagger \phi H^\dagger H$$



$$\mathcal{L}_{\rm HS} \supset \begin{cases} -\lambda_\chi\, \overline{\chi^c} \chi \phi \\ -f_{S\phi} S^\dagger S \Phi^\dagger \Phi \\ (\mathcal{D}_\mu \phi)^\dagger (\mathcal{D}^\mu \phi) \end{cases}$$

Hidden higgs boson - DM coupling
(DM is a fermion, a scalar or a vector)

Hidden Sector SSB:
- hidden higgs unstable
- DM stabilized by the remnant symmetry

Higgs mixing I, light ϕ: $m_\phi < 1$ GeV

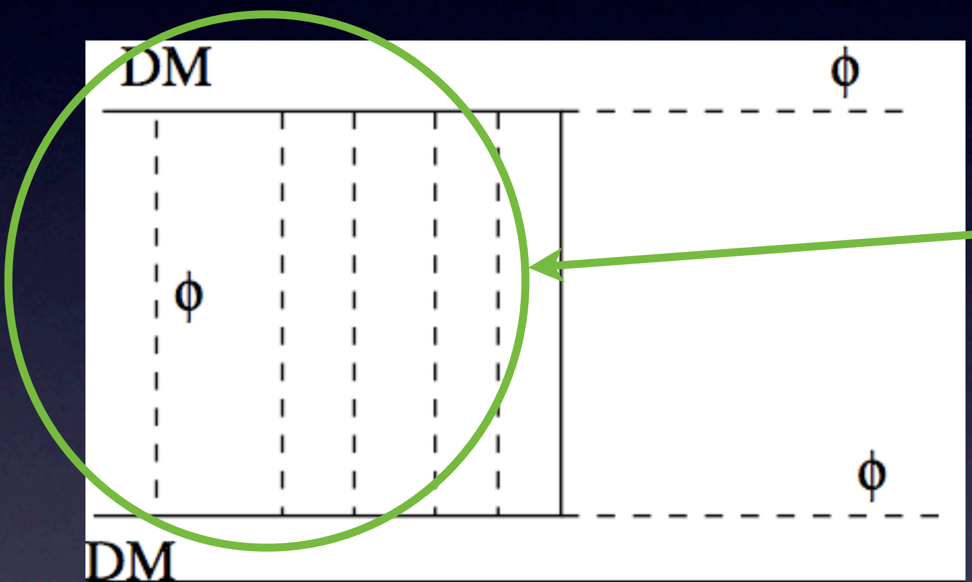
Arkani-Hamed et al '08, Chen et al. '09, March-Russell and West '09, K.Khori et al '09

The main motivation is to explain the positron excess:
- coupled mainly to leptons
- avoid overproduction of anti-protons

Phenomenology of the DM particle (Dirac fermion)

C.A., F.X. Josse-Michaux and N. Sahu, Phys.Lett.B691 (2010)

Higgs mixing parameterization ⟶ $\theta_{H\phi} \sim \mu_\phi v/(m_H^2)$

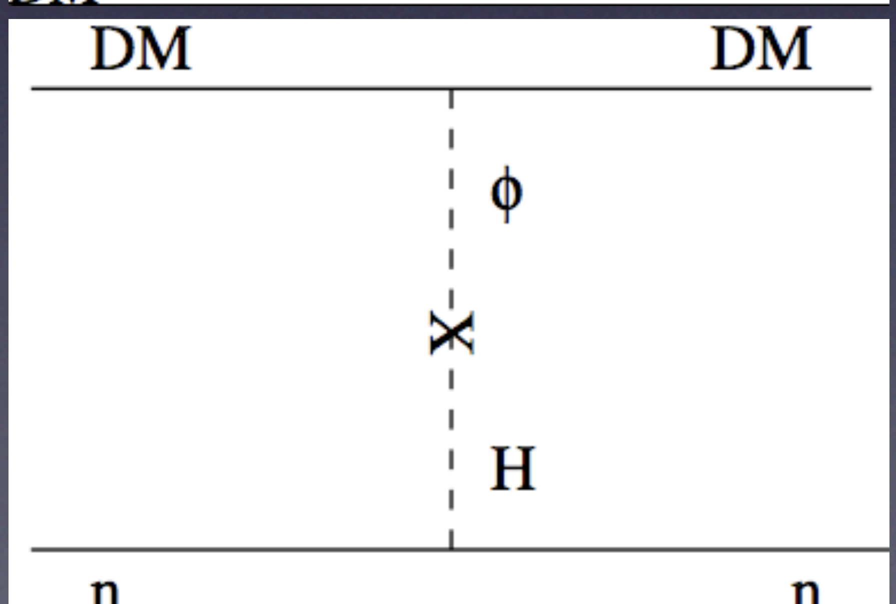


Relic abundance and indirect signals at present time

Sommerfeld enhancement

A. Sommerfeld 1931, J. Hisano, S. Matsumoto and M.M. Nojiri '04

$$\epsilon_\phi = m_\phi/(M_\chi \alpha_\chi)$$
$$\epsilon_v = \beta/\alpha_\chi$$
$$\alpha_\chi = \lambda_\chi^2/(4\pi)$$



Direct detection

$$\sigma_n^{SI} \propto \frac{\lambda_\chi^2 \theta_{H\phi}^2}{m_\phi^4}$$

the elastic cross-section is enhanced by the small ϕ mass

Direct detection and Sommerfeld enhancement

C.A., F.X. Josse-Michaux and N. Sahu, Phys.Lett.B691 (2010)

- Se averaged over the DM velocity distribution in the galactic halo
- both <Se> and total rate computed for v0 = 220 km/s

CDMSII upper bounds at 90% C.L.:

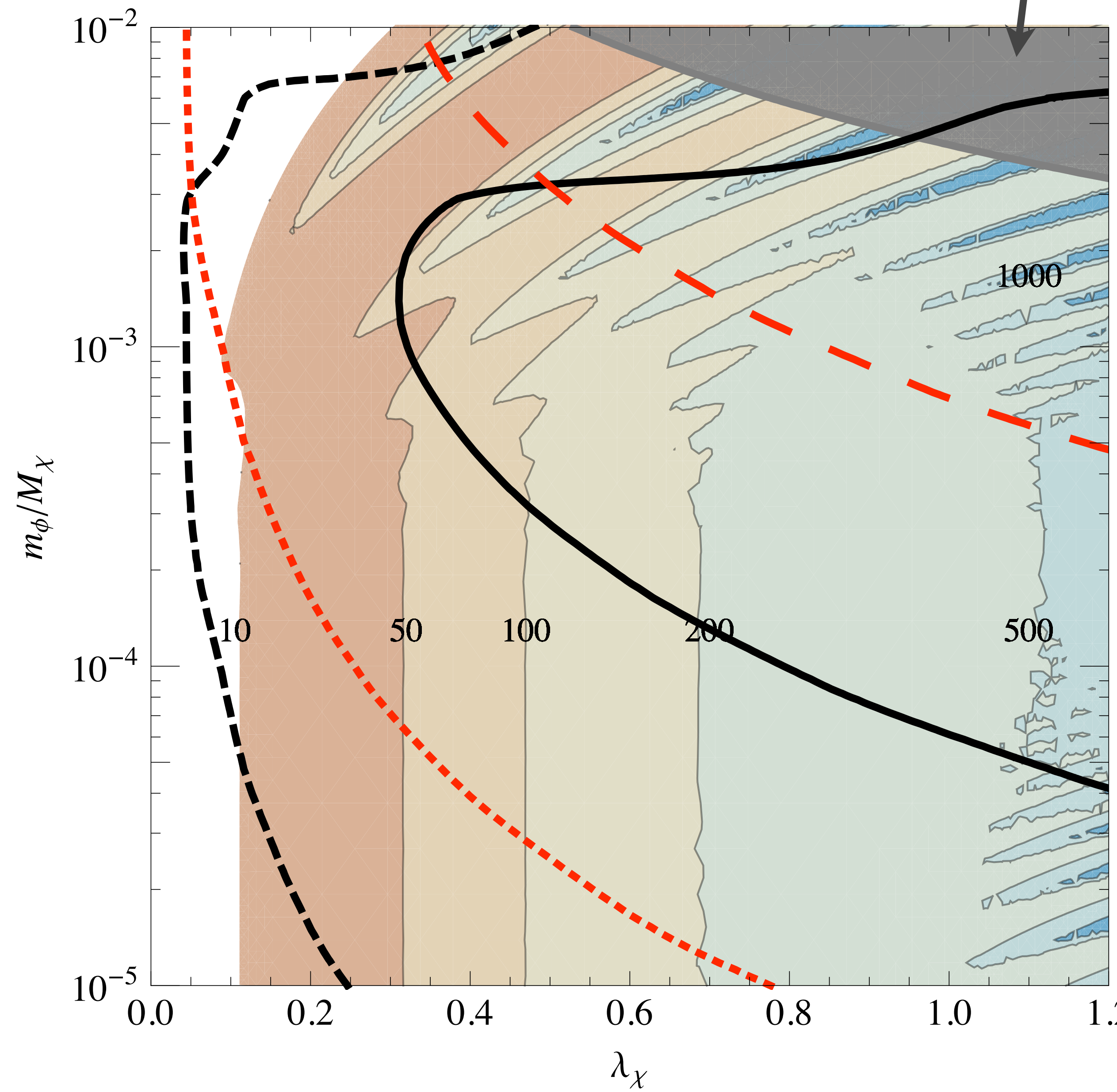
(red line) $m_\phi = 1\mathrm{GeV} \quad \theta_{H\phi} = 10^{-4}, 10^{-3}$

(black line) $m_\phi = 0.1\mathrm{GeV} \quad \theta_{H\phi} = 10^{-6}, 10^{-5}$

Maximum allowed <Se> depends on the Higgs mixing value

excluded by BBN

Hisano et al '09



$$\theta_{H\phi} > 10^{-7}/\sqrt{m_\phi/\mathrm{GeV}}$$

light higgs boson should decay before BBN

Kawasaki et al '05, Hisano et al '09

$\theta_{H\phi} < 10^{-2}$ from LEP

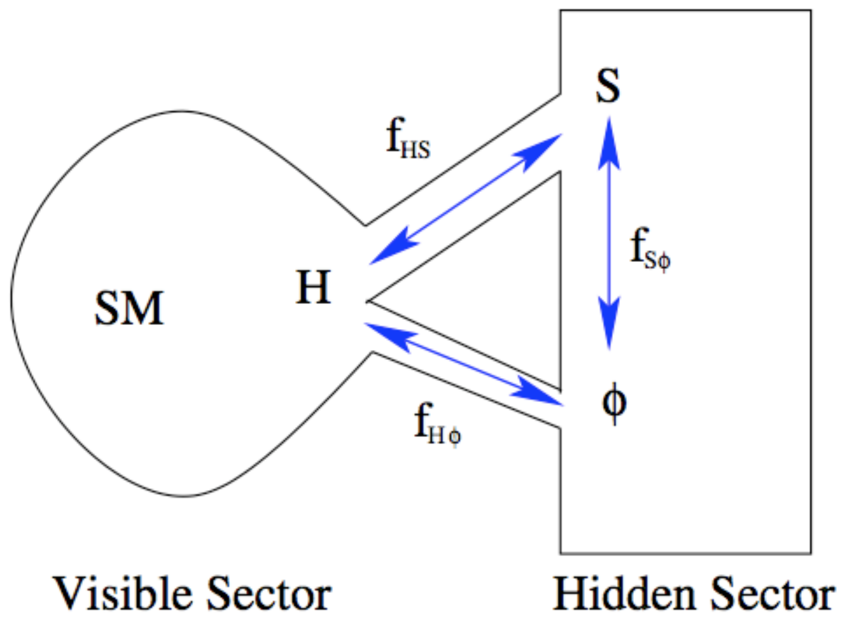
- proper to Higgs portal
- independent on the nature of the DM candidate even though scalar case less constrained

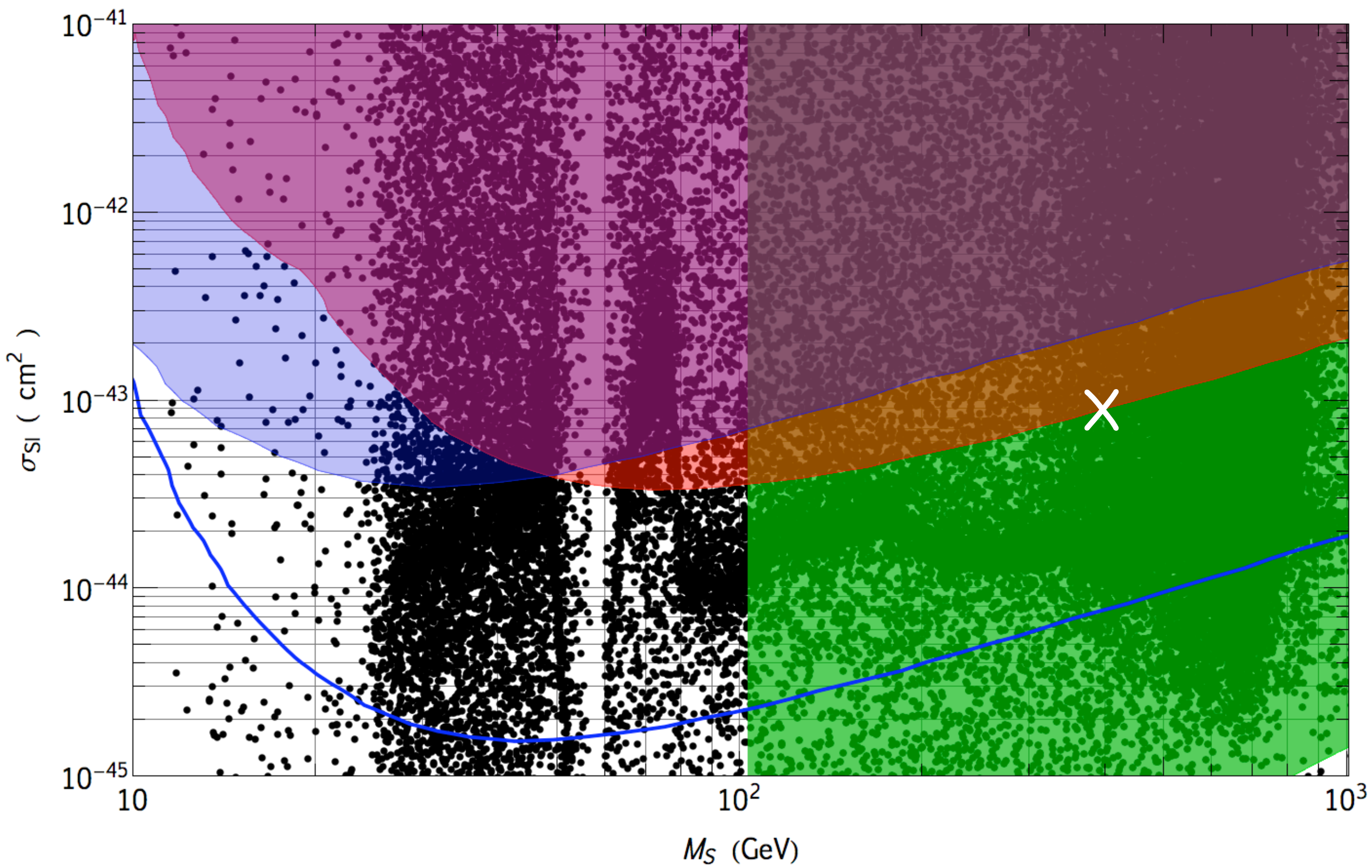
Nuclear scattering and light boson discussed in Finkbeiner et al. '09, Chen et al. '09, Cao et al '09 and Carroll et al. '09

Scalar DM candidate S

C.A., F.X. Josse-Michaux and N. Sahu, Phys.Rev.D82 (2010)
alternative model, i.e. K. Kohri, J. McDonald and N.Sahu, Phys.Rev.D81 (2010)

Hidden sector is a U(1): once ϕ takes a vev remnant Z2 symmetry to stabilize S





- Xenon10 and forecast for Xenon100
- CDMSII
- relic abundace in WMAP7 range
- <Se> satisfying CMB constraints, reionization and gamma ray bounds

Abdo et al '10; Cirelli et al '09; Huetsi et al '09; Galli et al '09; Slatyer et al. '09; Papucci, Strumia '09

The kinetic mixing is taken to be negligible

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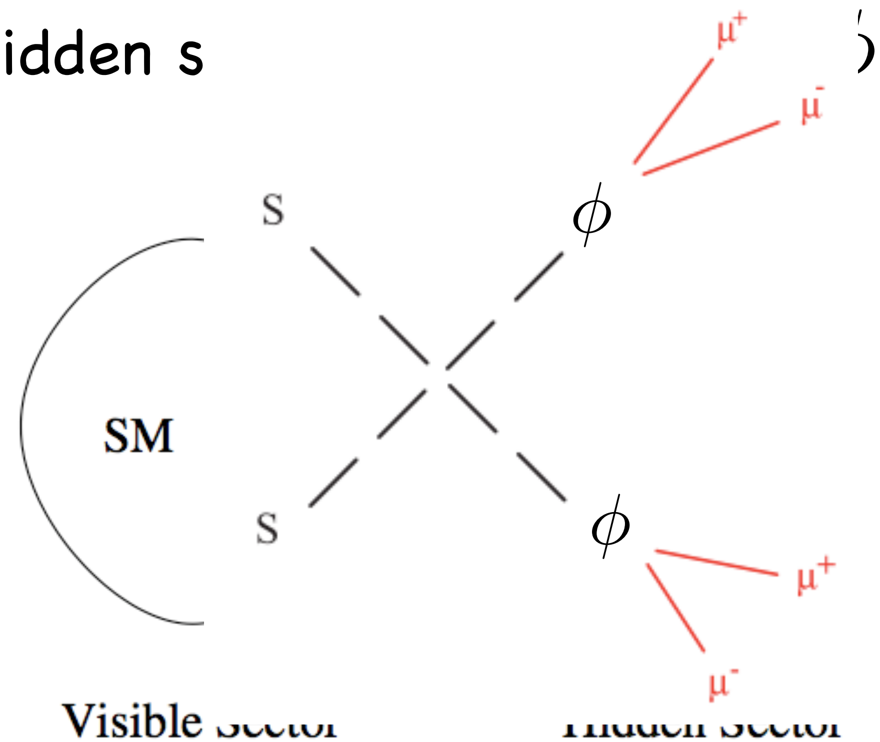
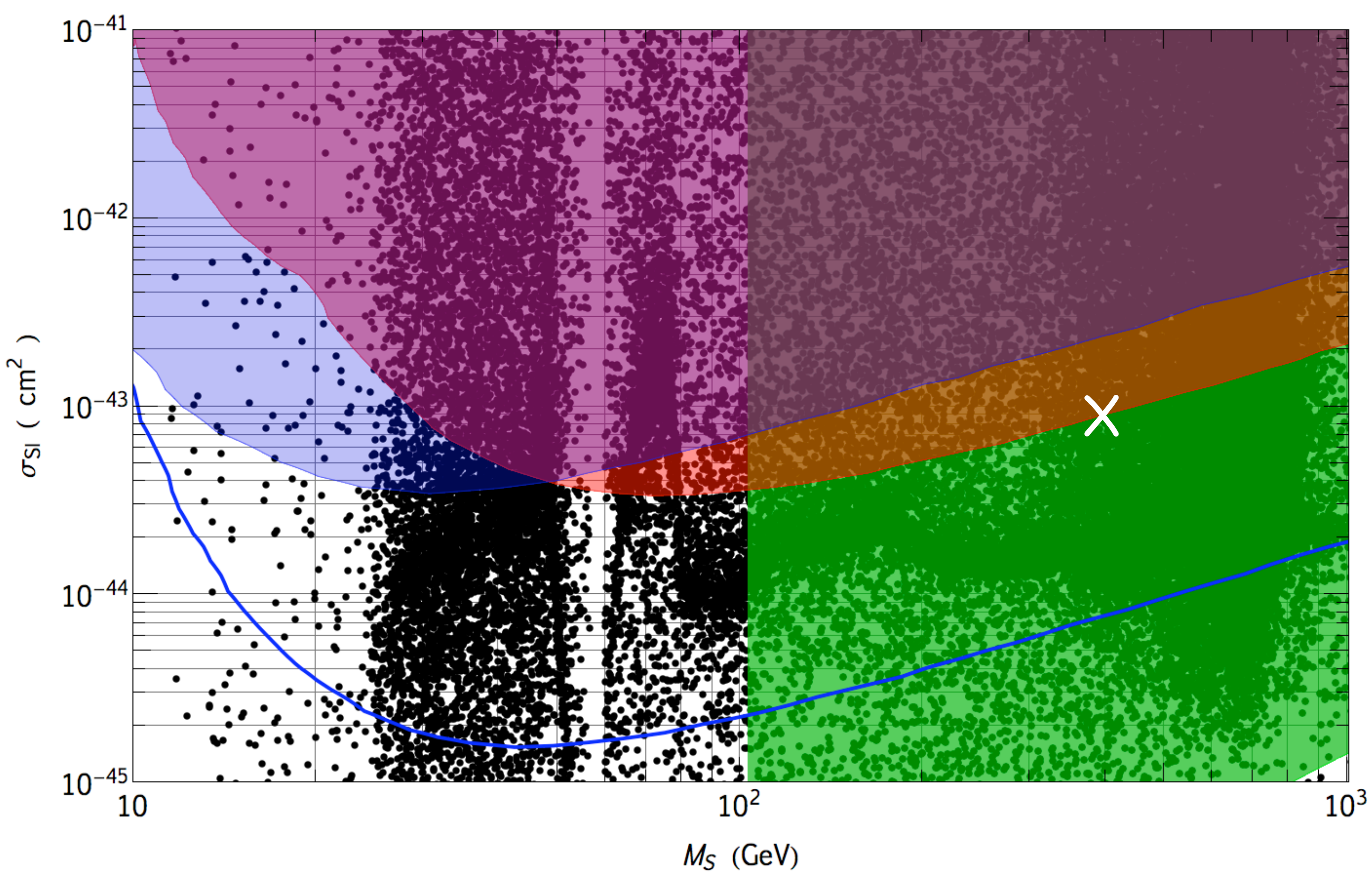
Hidden s ...) takes a vev remnant Z2 symmetry to stabilize S





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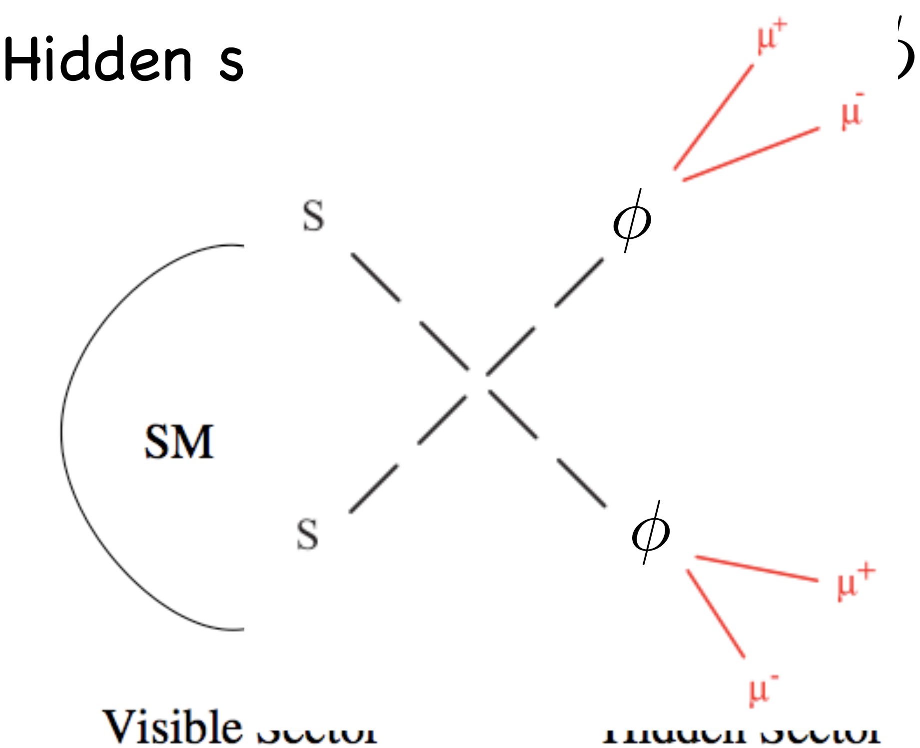
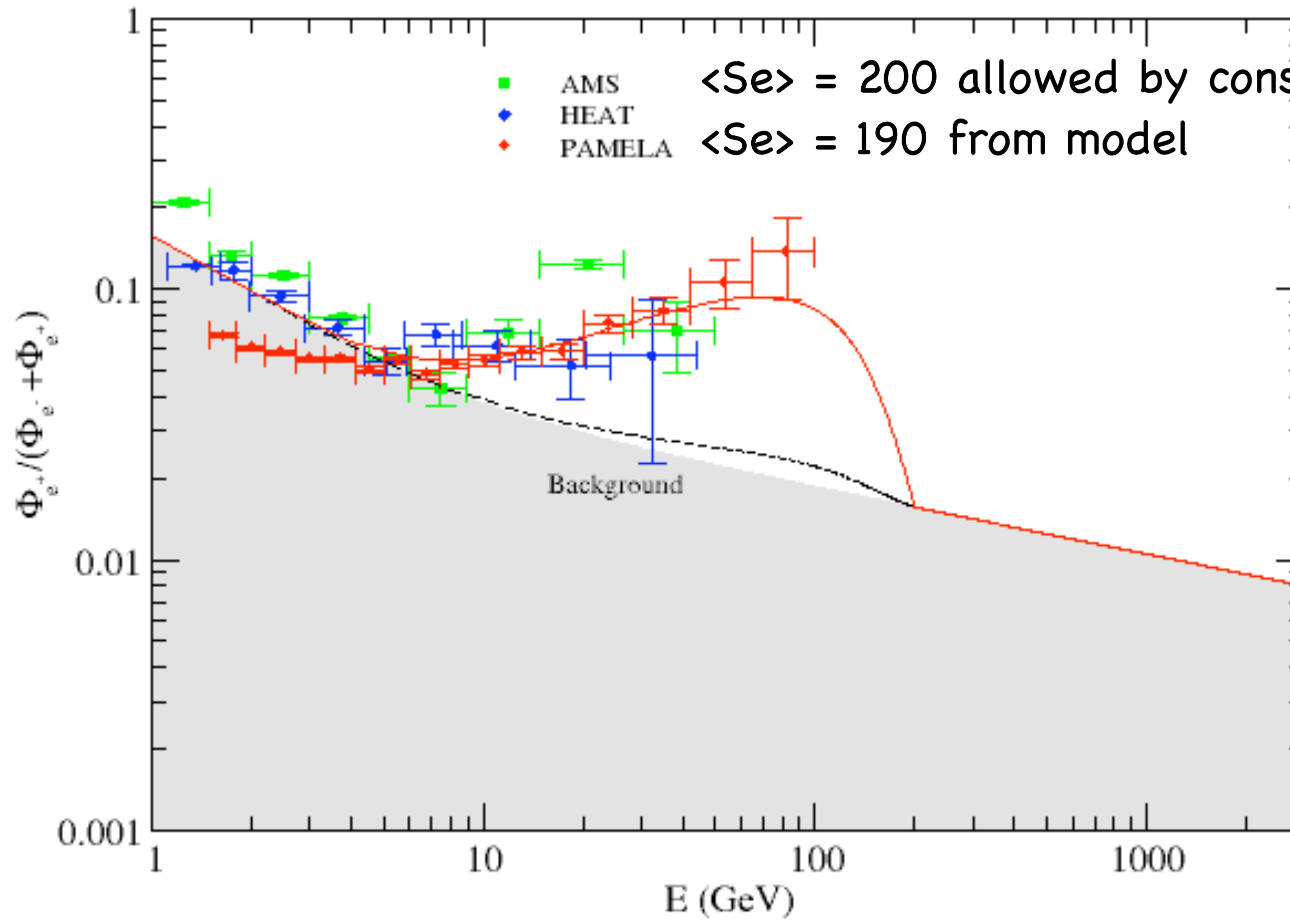
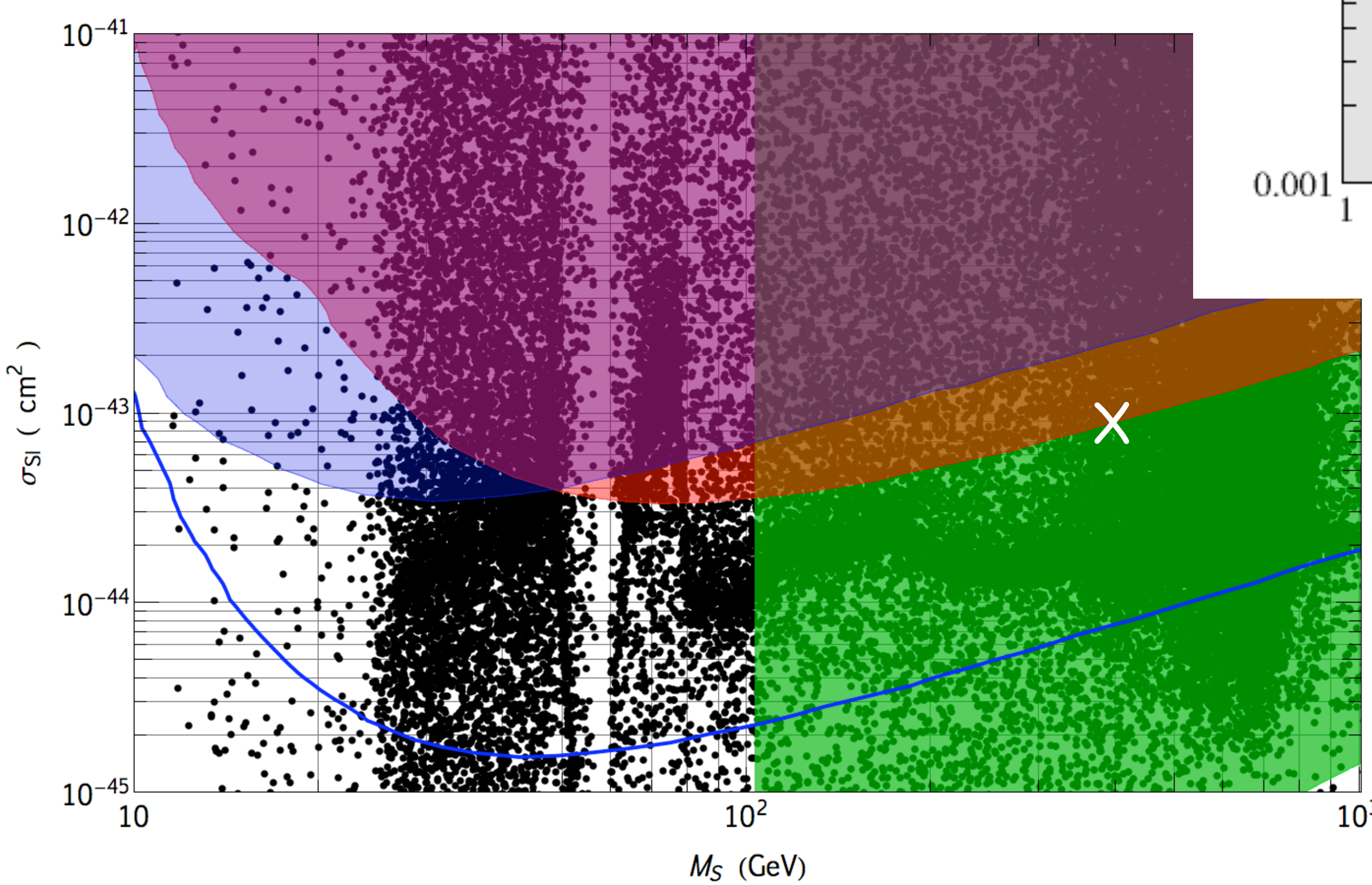


$-\mathcal{L}$

σ_S





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- relic abundance in WMAP7 range
- <Se> satisfying CMB constraints, reionization and gamma ray bounds

Abdo et al '10; Cirelli et al '09; Huetsi et al '09; Galli et al '09; Slatyer et al. '09; Papucci, Strumia '09

The kinetic mixing is taken to be negligible

- fine tuning between the breaking scale of the hidden sector and the ϕ mass
- ϕ mass needs to be stabilized from radiative corrections proportional to the DM mass (Supersymmetric scenario Arkani-Hamed et al. '09, Hooper and Tait '09, W. Wang et al. '09)

Higgs mixing II: unconstrained ϕ

Hidden SU(2) dark sector

C.A., T. Hambye, A. Ibarra and C. Weniger, JCAP 1003:024 (2010)
T. Hambye JHEP 0901:028 (2009)

$$\mathcal{L}_{\rm HS} = -\frac{1}{4} F^{\mu\nu} \cdot F_{\mu\nu} + (\mathcal{D}_\mu \phi)^\dagger (\mathcal{D}^\mu \phi) - \mu_\phi^2 \phi^\dagger \phi - \underbrace{\lambda_\phi (\phi^\dagger \phi)^2}$$

ϕ gets a vev

SU(2) ⟶ SO(3)

- DM candidates = 3 degenerate massive gauge bosons V
- DM stable by means of the custodial symmetry
- Higgs mixing does not spoil the stability of the DM

$$M_V = \frac{g_\phi v_\phi}{2}$$

- Correct relic abundance for a large mass spectrum: from few GeV up to O(10 TeV) scale
- Elastic cross-section is mediated only by the Higgs portal and is in the reach of sensitivity of CDMSII (again enhanced for light hidden Higgs)

Decaying Vector Dark Matter and GUT scale

C.A., T. Hambye, A. Ibarra and C. Weniger, JCAP 1003:024 (2010)

- DM is stable due to an accidental symmetry
- higher order operator are expected to destabilize the DM (as the proton in the SM)

↓ 6 dimensional operators

Eichler '89; Nardi, Sannino, Strumia '08; Hamagushi, Shirai, Yanagida '08; Arvanitaki et al. '08; Rudermann Volansky '09...

(A) $$\frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\phi\,\mathcal{D}_\mu H^\dagger H$$

(B) $$\frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\phi\,H^\dagger\mathcal{D}_\mu H$$

(C) $$\frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\mathcal{D}_\nu\phi\,F^{\mu\nu Y}$$

(D) $$\frac{1}{\Lambda^2}\,\phi^\dagger F^a_{\mu\nu}\frac{\tau^a}{2}\phi F^{\mu\nu Y}$$

- V are unstable and decay
- if Λ is the GUT scale then $\tau \sim 10^{26}\mathrm{s}$

$$\tau \sim 2\times 10^{26}\,\mathrm{s}\left(\frac{\mathrm{TeV}}{m_{\mathrm{DM}}}\right)^5\left(\frac{M}{10^{16}\,\mathrm{GeV}}\right)^4$$

All these operators lead to gamma-ray lines accompanied by an Higgs boson

Benchmark	M_A	g_ϕ	v_ϕ	M_η	M_h	$\sin\beta$
1	300 GeV	0.55	1090 GeV	30 GeV	150 GeV	≈ 0
2	600 GeV	0.6	2000 GeV	30 GeV	120 GeV	≈ 0
3	14 TeV	12	2333 GeV	500 GeV	145 GeV	≈ 0
4	1550 GeV	2.1	1457 GeV	1245 GeV	153 GeV	0.25

Case C

Benchmark	$Z\eta$	$\gamma\eta$	Zh	γh
1	0.19	0.81	0	0
2	0.22	0.78	0	0
3	0.23	0.77	0	0
4	0.028	0.79	0.041	0.14

Benchmark	$\eta\eta$	$h\eta$	hh	$\gamma\eta$	$Z\eta$	γh	Zh
1	-	0.09	-	0.04	0.02	0.65	0.20
2	-	0.04	0.62	0.002	0.003	0.15	0.18
3	-	0.04	0.80	3×10^{-6}	0.002	0.0003	0.16

Case A/B

Case D

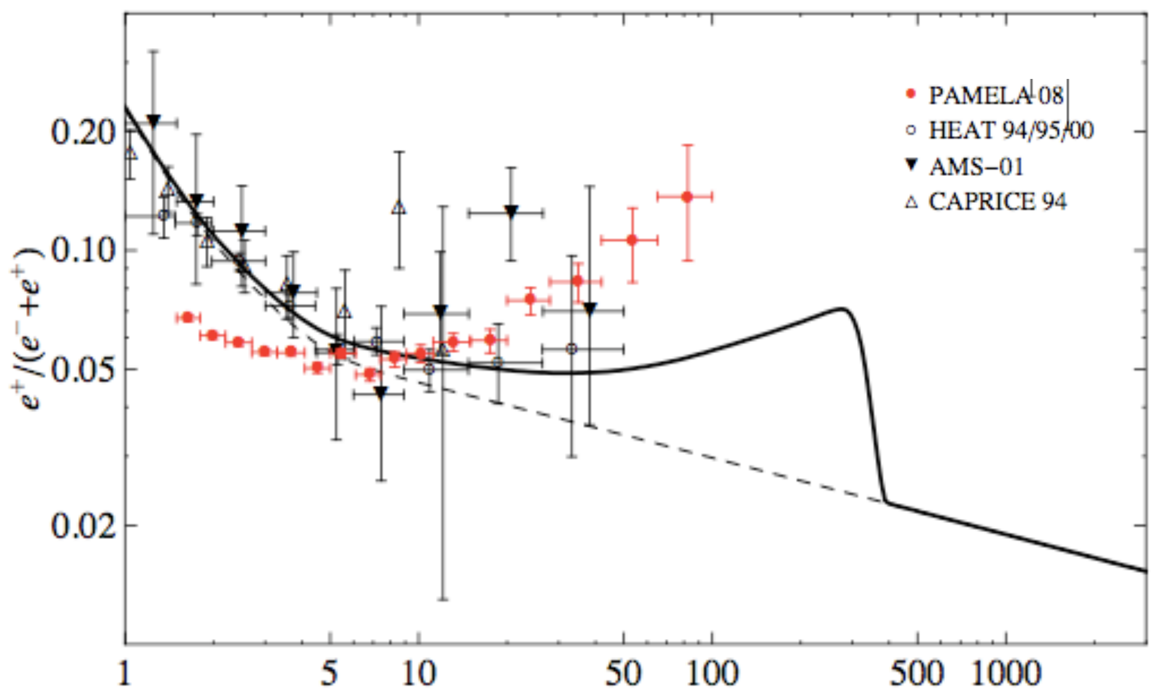
k	$Z\eta$	Zh	$\gamma\eta$	W^+W^-	$\nu\bar\nu$	e^+e^-	$u\bar u$	$d\bar d$
1	0.01	0.005	0.04	0.02	0.09	0.39	0.29	0.15
2	0.019	0.004	0.036	0.014	0.072	0.35	0.39	0.12
3	0.22	0.0002	0.73	0.0005	0.003	0.016	0.018	0.005

No need of boost

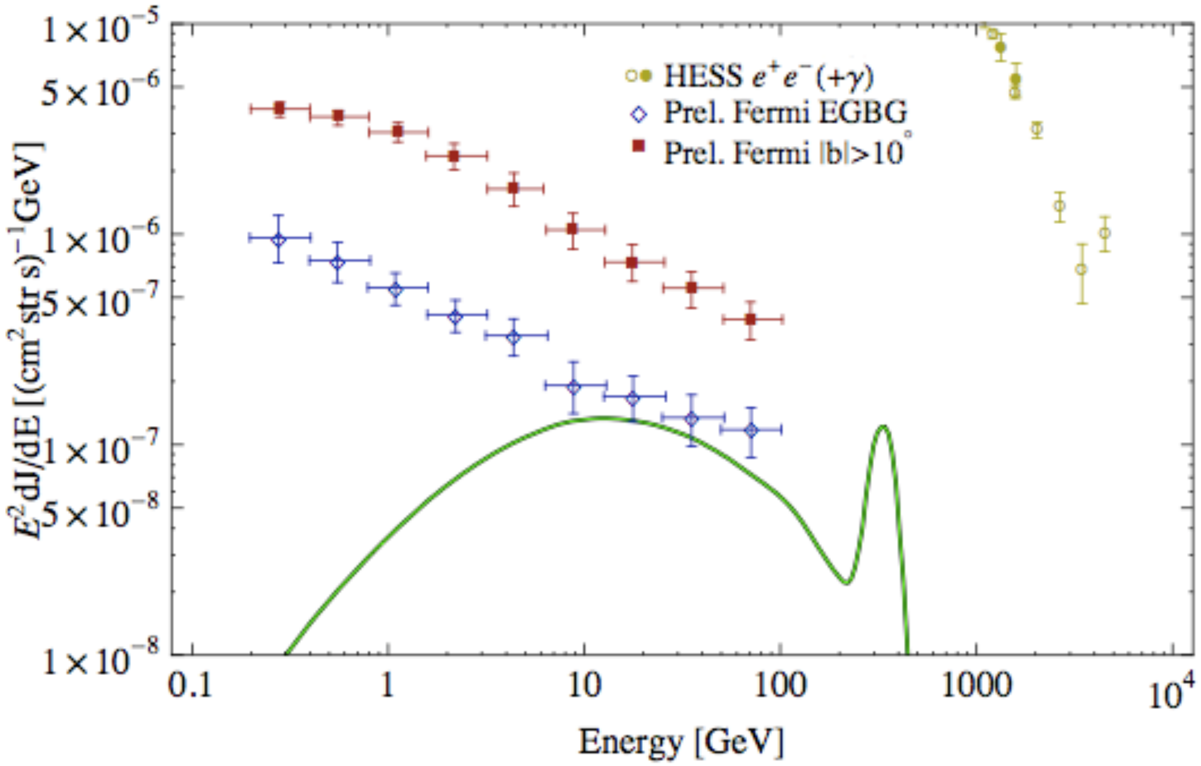
Monochromatic γ lines

C.A., T. Hambye, A. Ibarra and C. Weniger, JCAP 1003:024 (2010)

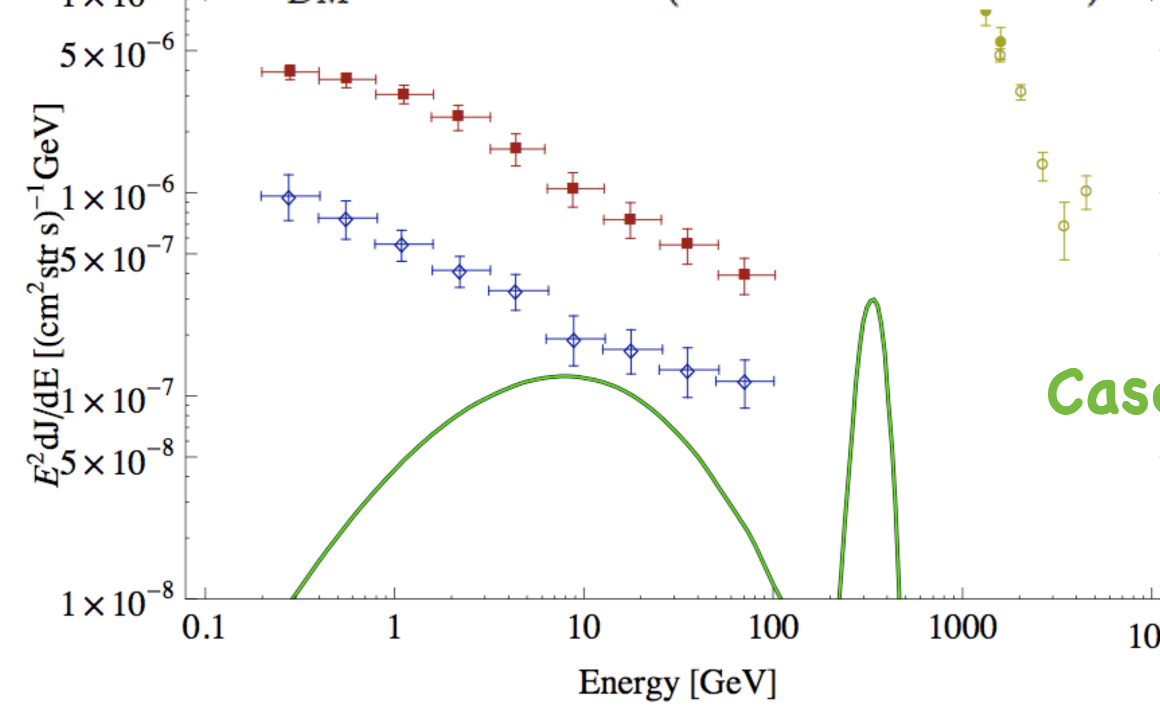
$0 \leq l \leq 360°, 10° \leq |b| \leq 90°$



Case D $\tau_{DM} = 6.7 \times 10^{26}$ s ($\Lambda = 1.5 \times 10^{16}$ GeV)

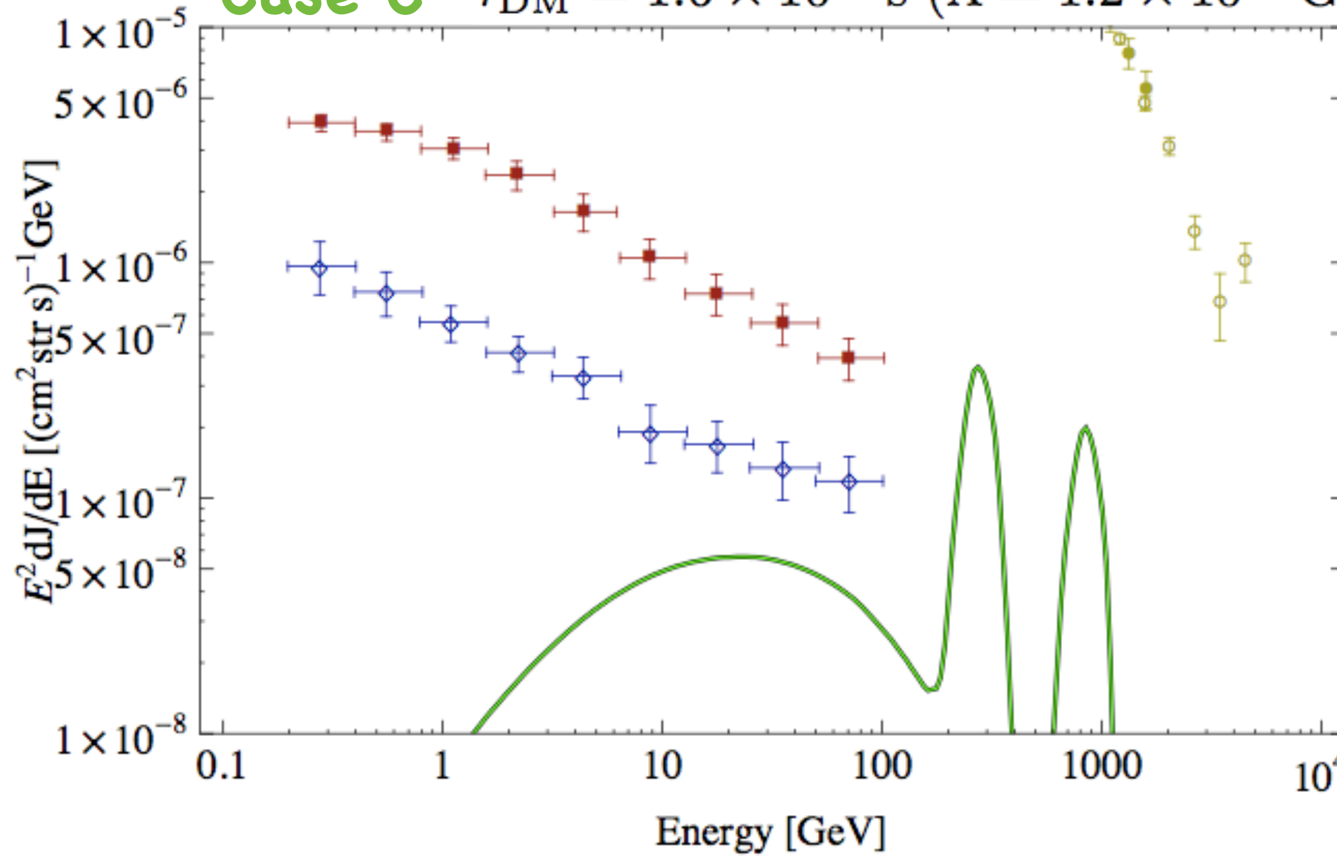


$\tau_{DM} = 1.1 \times 10^{27}$ s ($\Lambda = 3.7 \times 10^{15}$ GeV)



Case A/B

Case C $\tau_{DM} = 1.6 \times 10^{27}$ s ($\Lambda = 1.2 \times 10^{16}$ GeV)



Summary

- Hidden Dark Matter sector connected with the SM through the Higgs portal
- Gauged hidden sector spontaneously broken by the hidden higgs (DM stable by means of the remnant symmetry)

Case I: light hidden boson

- Annihilating dark matter, whose cross-section is boosted by the Sommerfeld effect
- A light hidden boson boost also the elastic spin independent nuclear cross-section
- allowed Sommerfeld boost depends on the Higgs portal coupling
- scalar candidate con explain the PAMELA excess and being in the reach of CDMSII

Case II: unconstrained hidden boson

- Vectorial DM whose decay is induced by 6-dim operators at the GUT scale
- It can not fully account for the positron excess
- Smoking gun signatures: prominent gamma lines accompanied by the Higgs bosons in the experimental range

Thanks !

Backup Slides

Sommerfeld enhancement

C.A., F.X. Josse-Michaux and N. Sahu, Phys.Lett.B691 (2010)

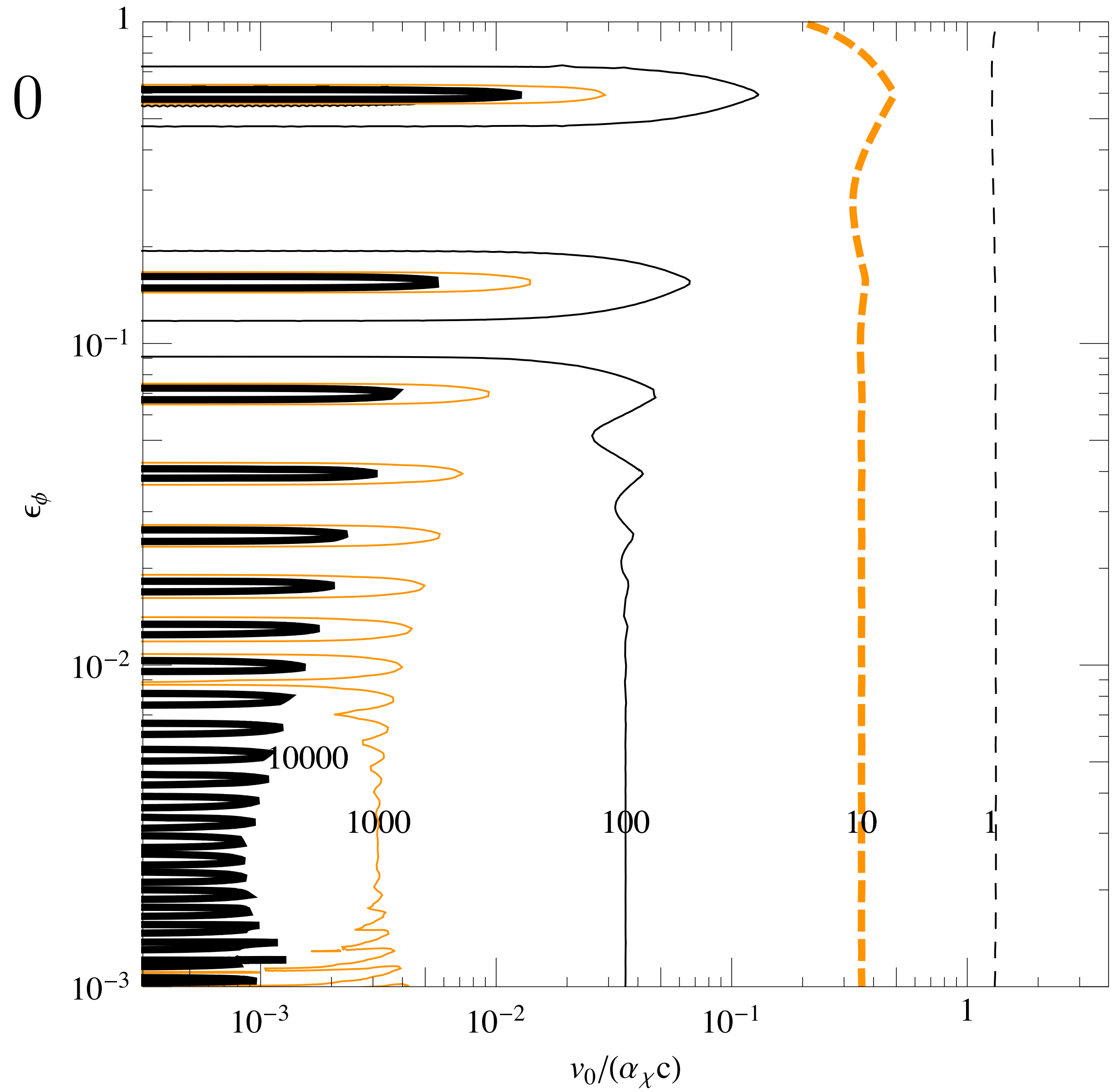
- non perturbative mechanism: distortion of the two-body wavefunction away from plane wave when the kinetic energy is low enough that a long-range potential is relevant

- attractive Yukawa potential provides enhancement of the annihilation cross-section

$$V(r) = -\left(\frac{\alpha_\chi}{r}\right) e^{-m_\phi r}$$

$$\psi(r)'' - M_{DM} V(r)\psi(r) + M_{DM}^2 \beta^2 \psi(r) = 0$$

$$S_e = \left|\frac{\psi(\infty)}{\psi(0)}\right|^2$$



Averaged over an isothermal Maxwellian velocity distribution for the galactic halo:

$$\langle S_e \rangle = \frac{4}{\sqrt{\pi}} \left(\frac{\alpha_\chi c}{v_0}\right)^3 \int_0^\infty d\epsilon_v \, \epsilon_v^2 e^{(-\epsilon_v^2 \alpha_\chi^2 c^2 / v_0^2)} S_e(\epsilon_v, \epsilon_\phi)$$

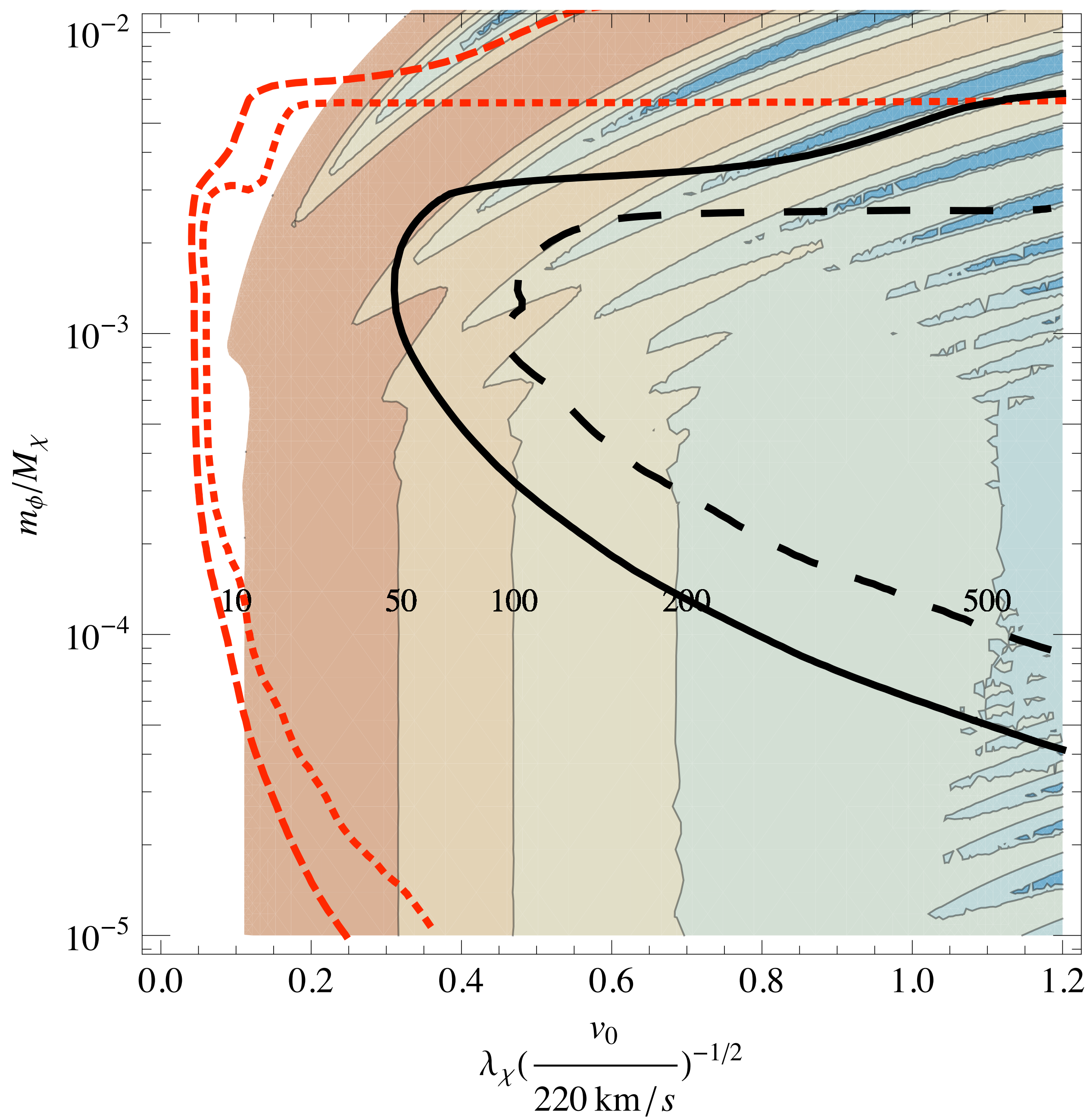
C.A., F.X. Josse-Michaux and N. Sahu, Phys.Lett.B691 (2010)

Direct detection - differential rate:

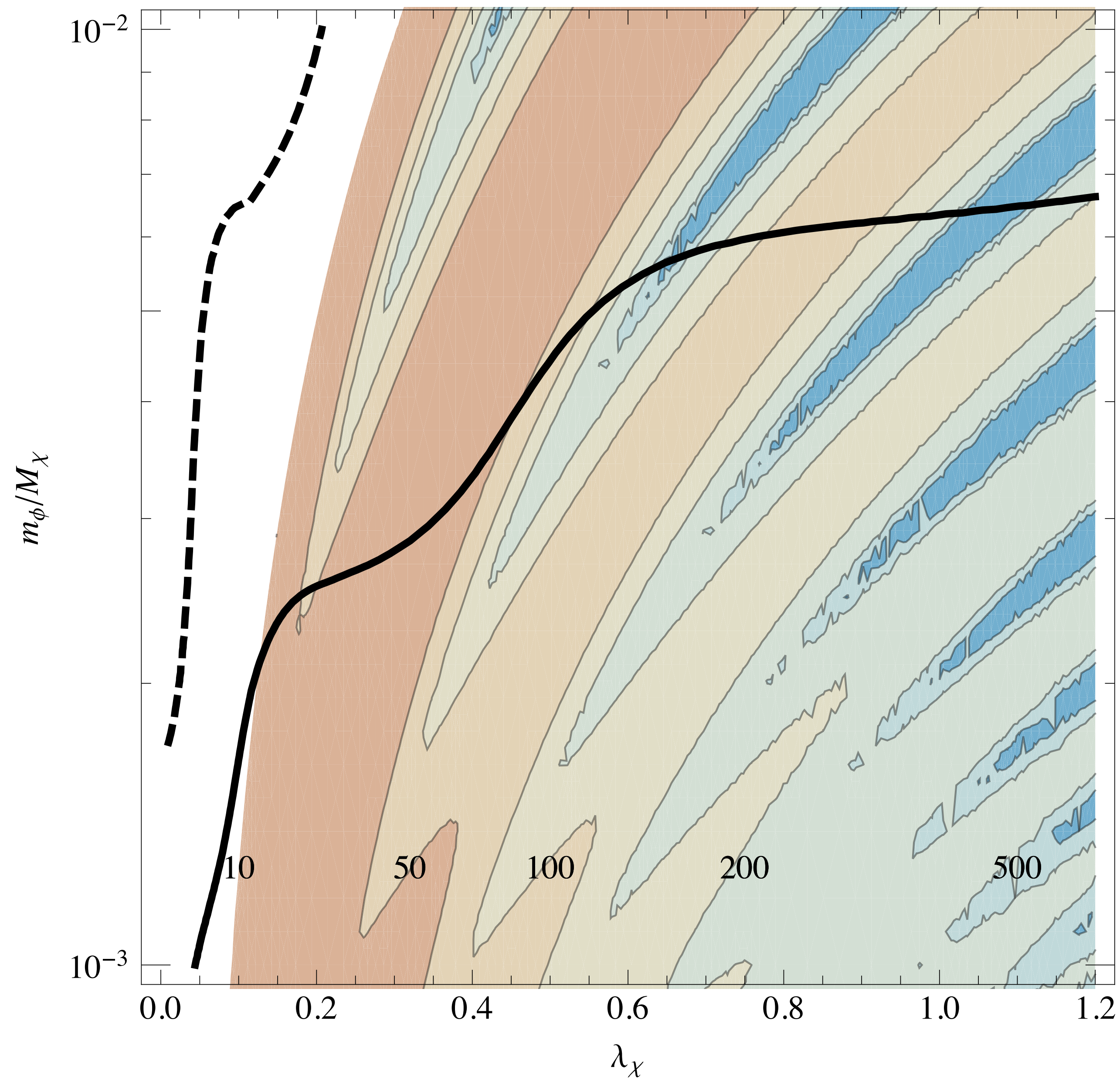
$$\frac{dR}{dE_r} \propto \frac{\mu_n^2 f_n^2 m_n^2}{v^2} \frac{\lambda_\chi^2 c}{4\pi v_0} \frac{\theta_{H\phi}^2}{m_\phi^4} \frac{1}{y} F(x,y,z)$$

$$x = v_{\rm min}/v_0$$
$$y = v_{\rm obs}/v_0$$
$$z = v_{\rm esc}/v_0$$

dependence on astro parameters

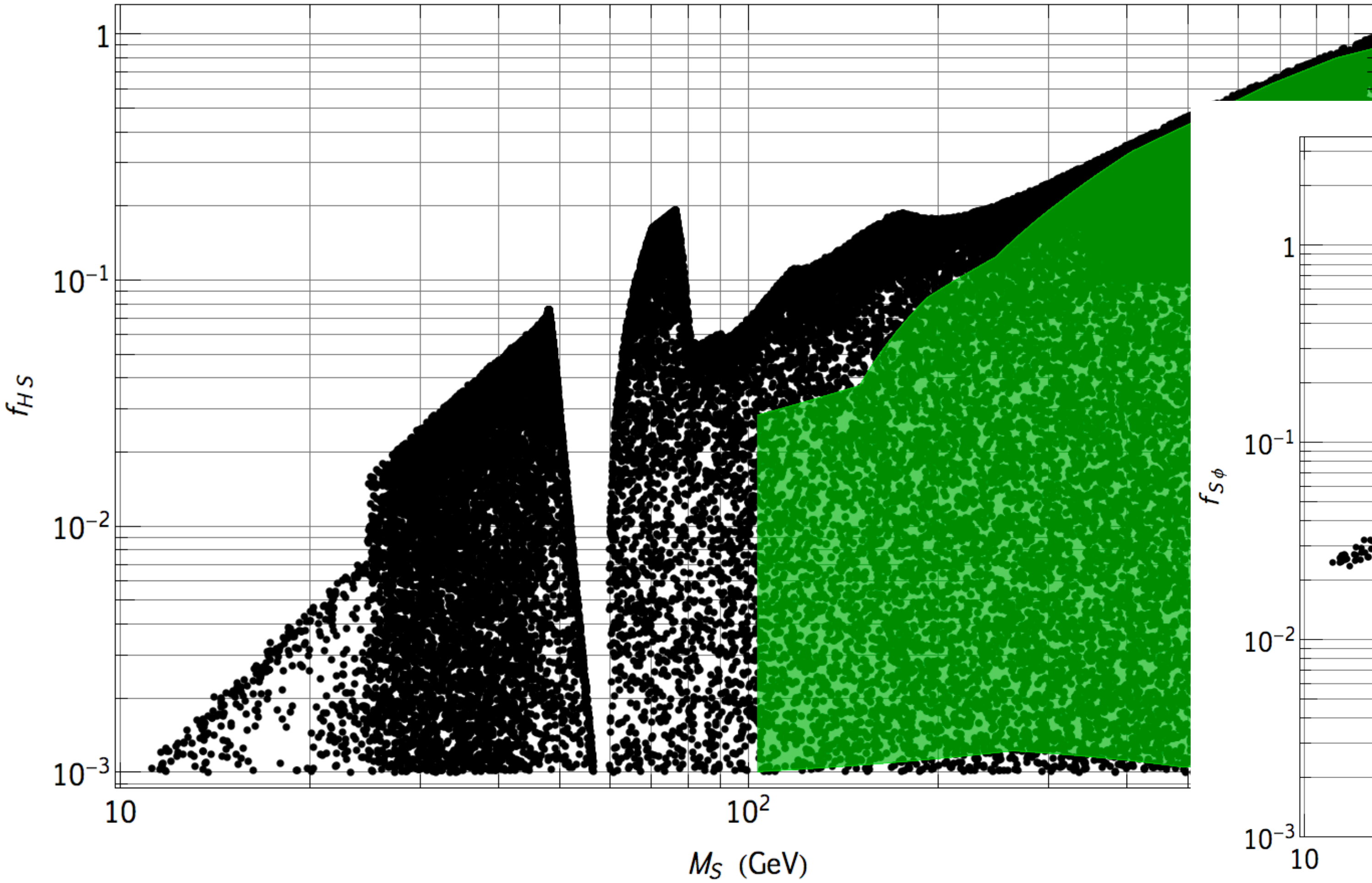


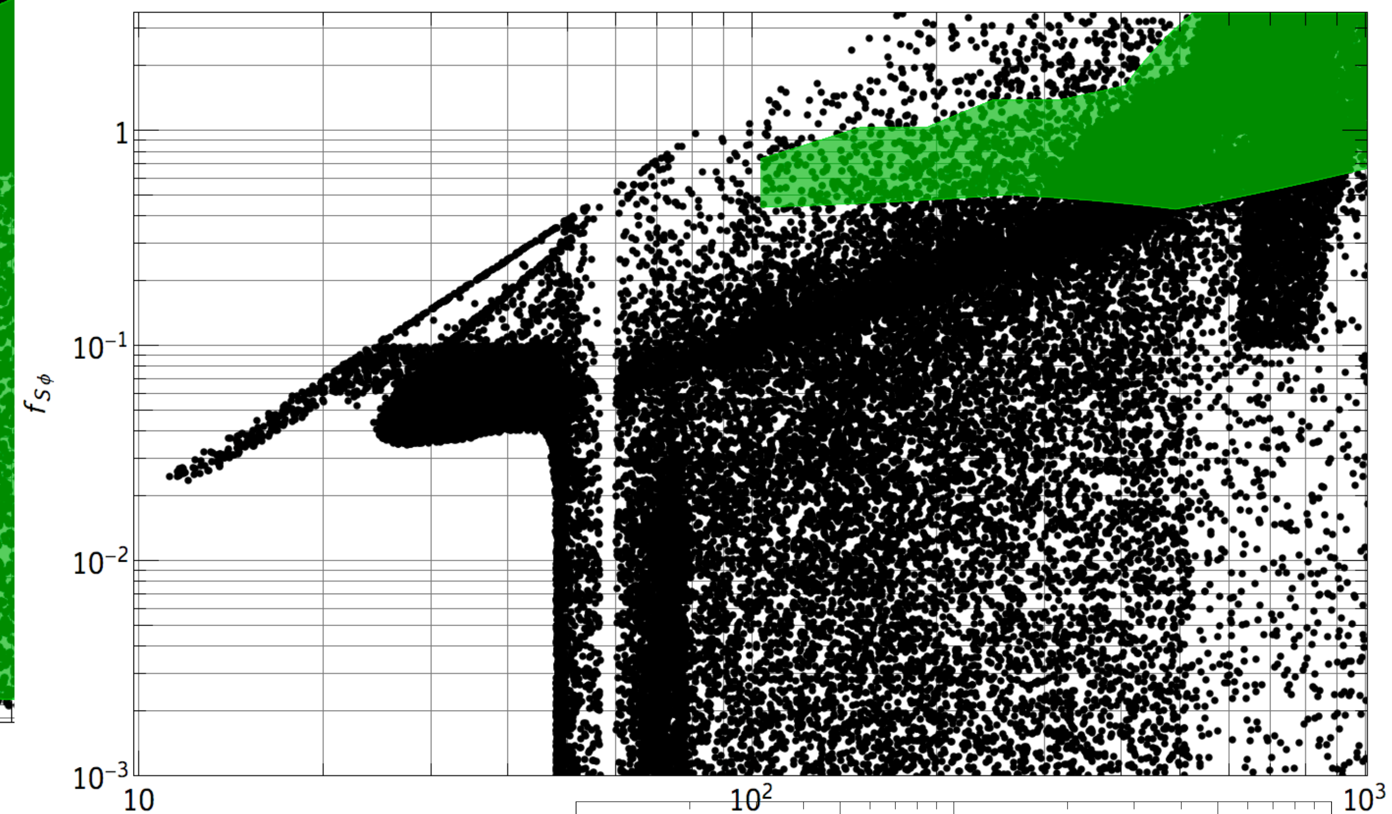
DM mass fixed at 100 GeV

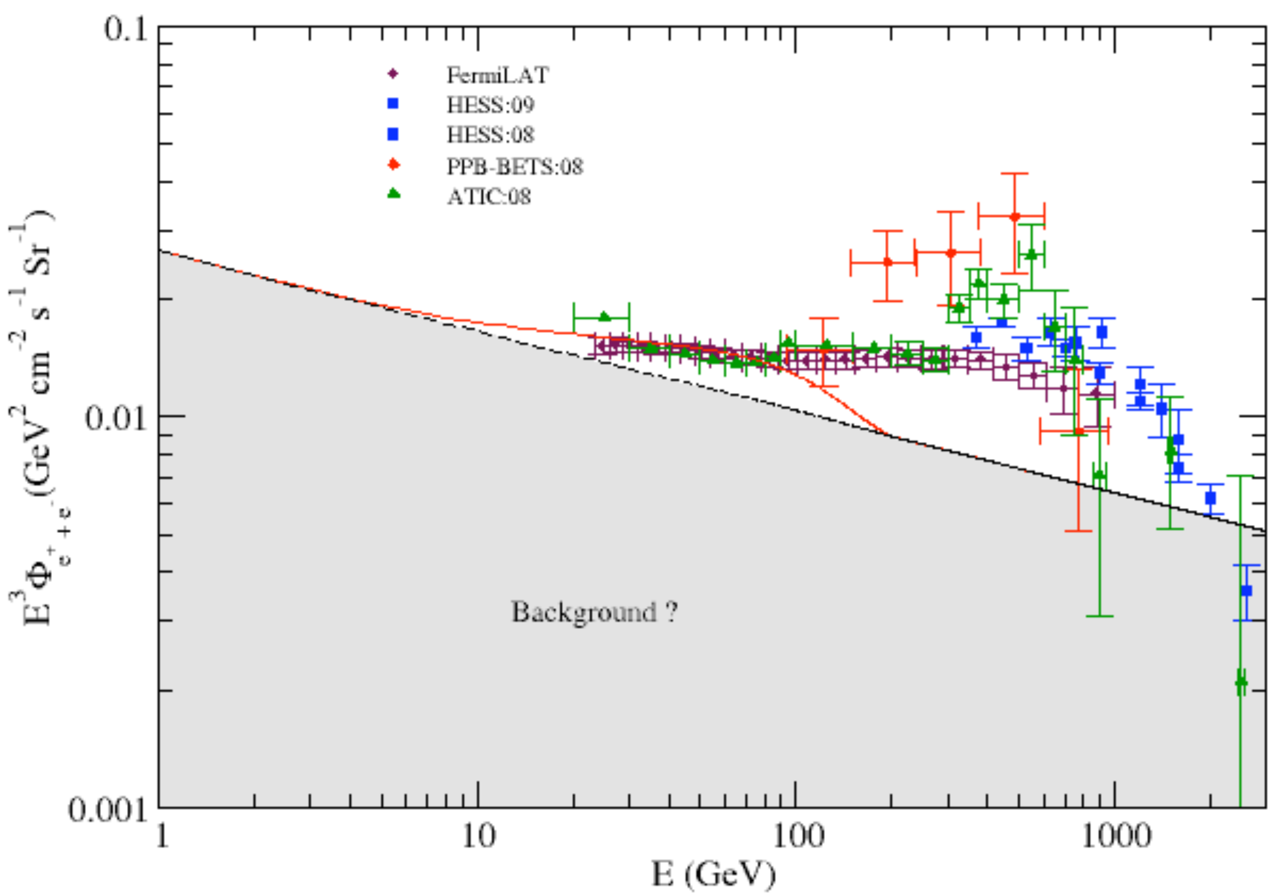


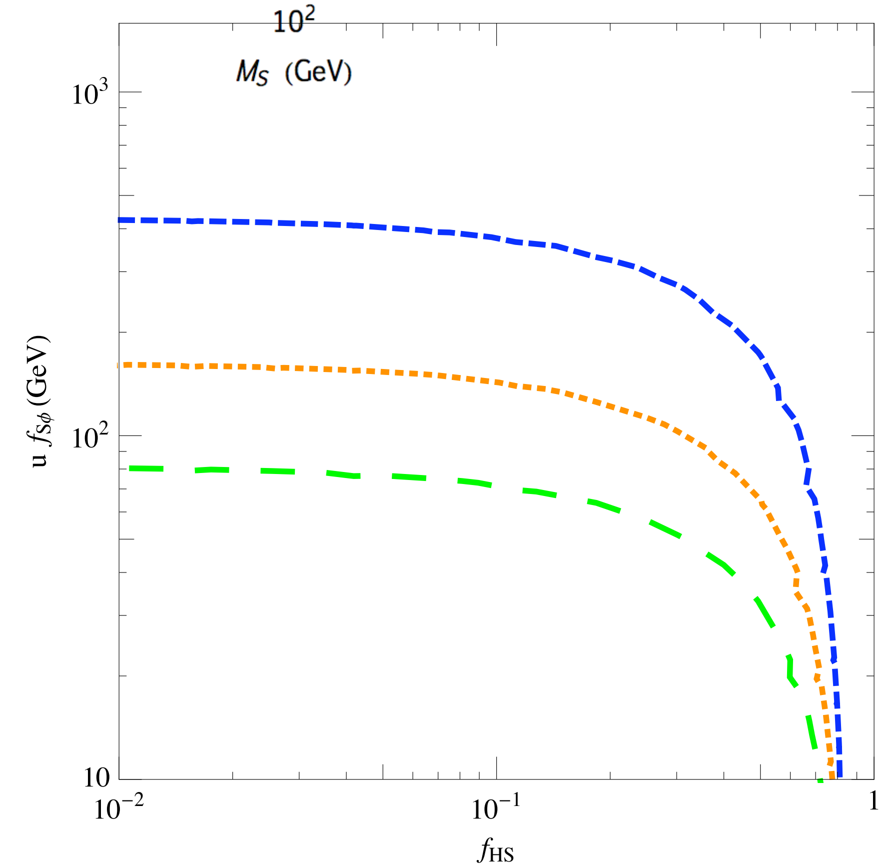
Scalar DM candidate

C.A., F.X. Josse-Michaux and N. Sahu, Phys.Rev.D82 (2010)





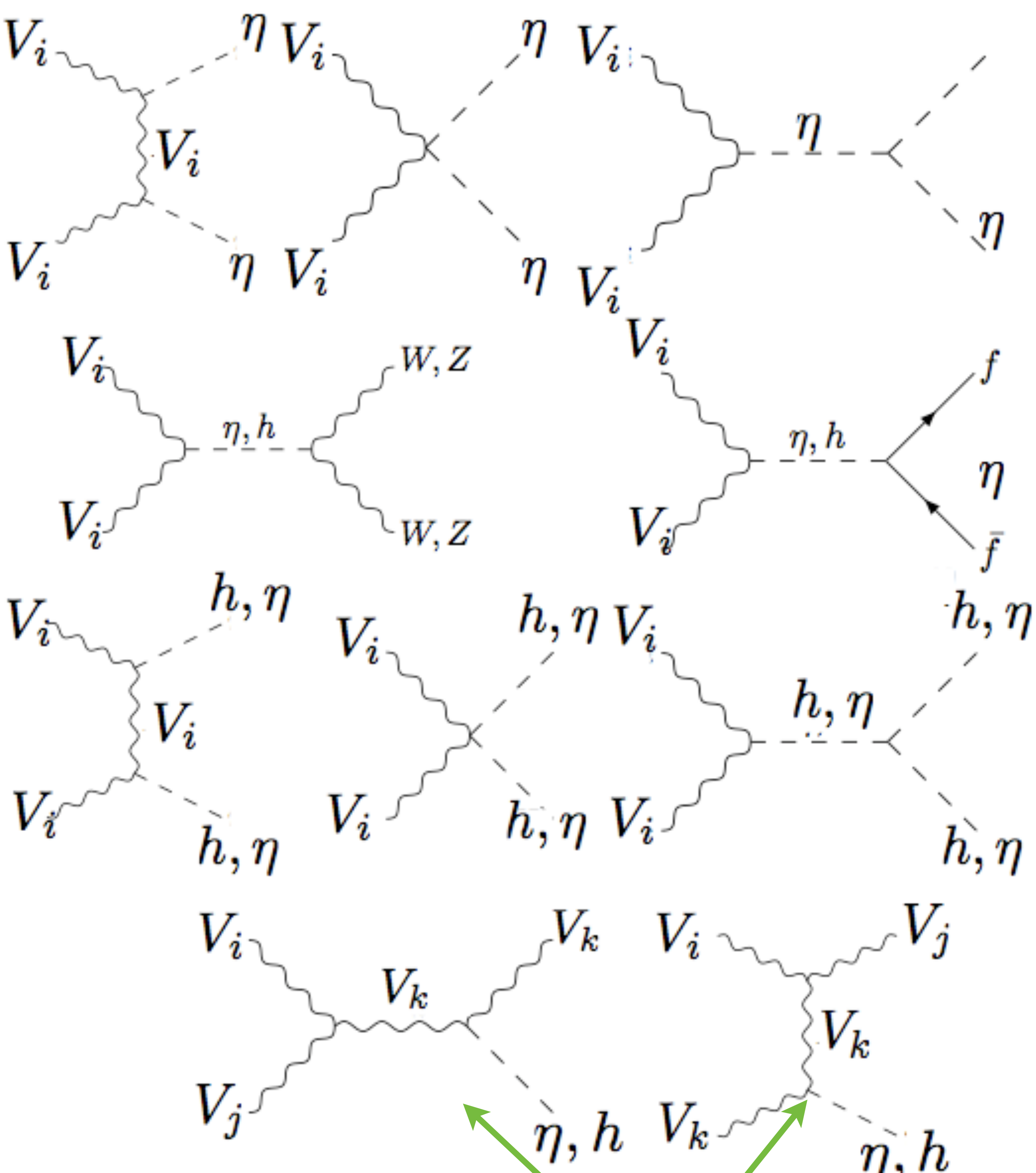




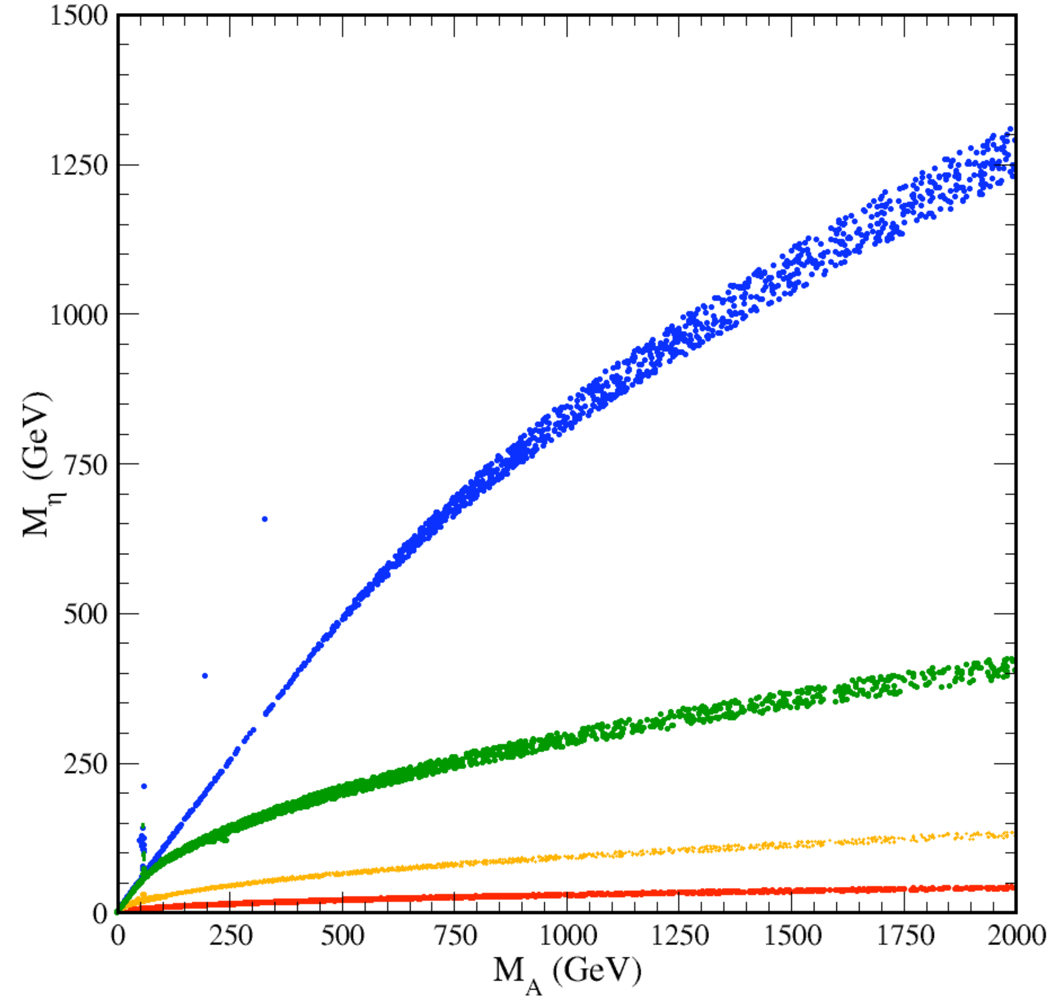
Hidden Vector DM

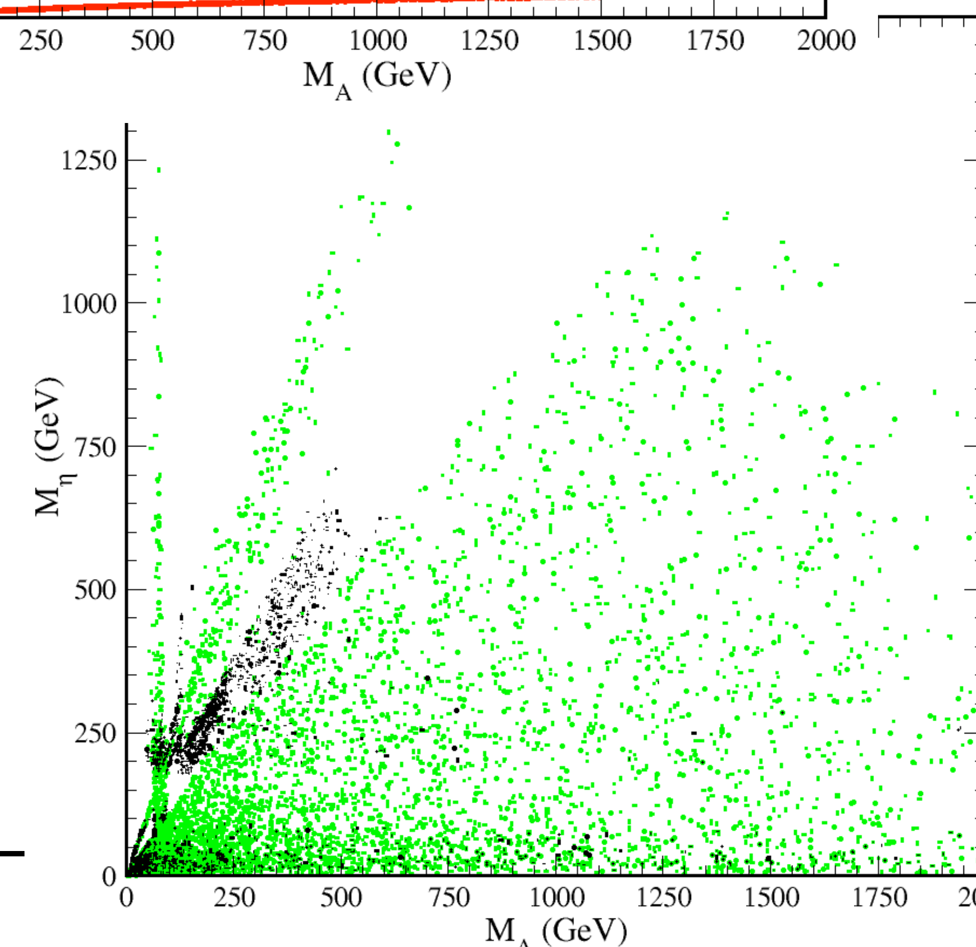
C.A., T. Hambye, A. Ibarra and C. Weniger, JCAP 1003:024 (2010)
T. Hambye JHEP 0901:028 (2009)

Relic abundance



3 DM particles

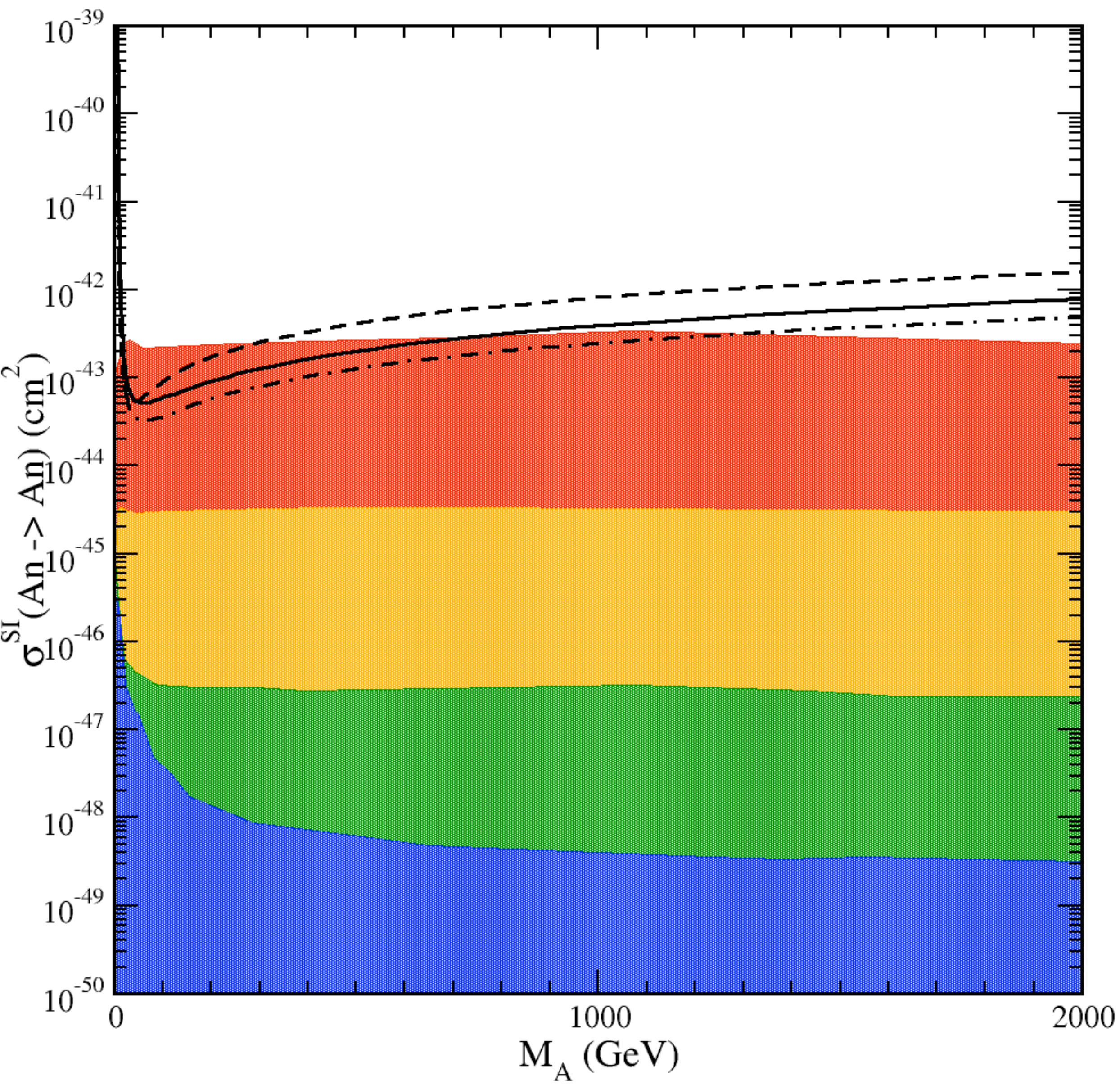


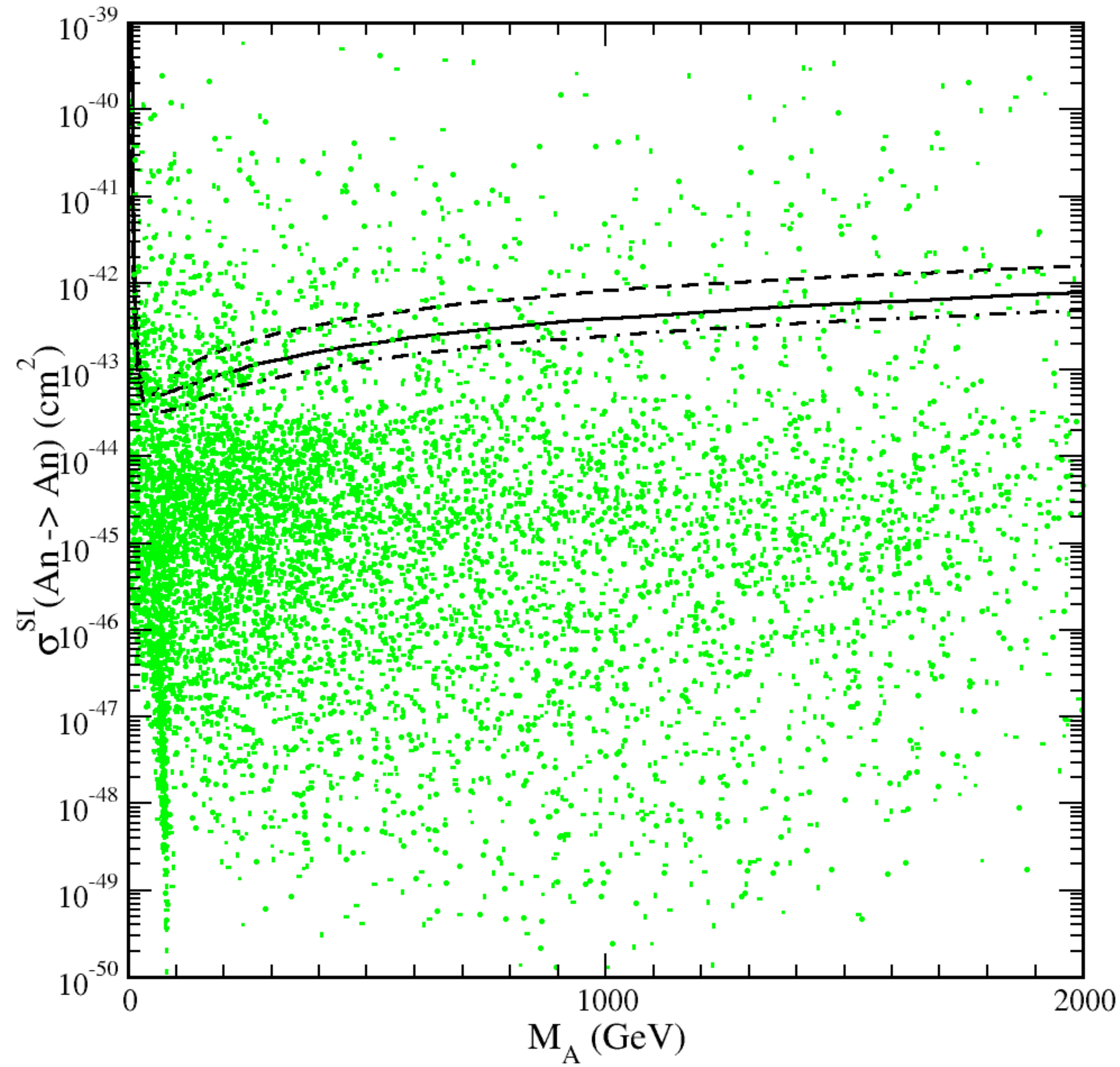


C.A., T. Hambye, A. Ibarra and C. Weniger, JCAP 1003:024 (2010)
T. Hambye JHEP 0901:028 (2009)

Spin independent elastic cross-section on nucleon

$$\sigma^{SI}(Vn \to Vn) = \frac{1}{64\pi^2} f^2 g_\phi^4 \sin^2 2\beta \; m_n^2 \frac{v_\phi^2}{v^2} \frac{(m_\phi^2 - m_H^2)^2}{m_\phi^4 m_H^4} \frac{\mu_n^2}{M_V^2}$$





FermiLAT collaboration ⟶ bounds on gamma lines

A.Abdo, M. Ackermann, M. Ajello et al. PRL104 (2010)

Fermi Large Area Telescope Search for Photon Lines from 30 to 200 GeV and Dark Matter Implications

E_γ (GeV)	95%CLUL (10^{-9} cm^{-2}s^{-1})	$\langle\sigma v\rangle_{\gamma\gamma}$ [γZ] (10^{-27} cm^{3}s^{-1}) NFW	Einasto	Isothermal	$\tau_{\gamma\gamma}$ [γZ] (10^{28} s) NFW	Einasto	Isothermal
30	3.5	0.3 [2.6]	0.2 [1.9]	0.5 [4.5]	17.6 [4.2]	17.8 [4.2]	17.5 [4.2]
40	4.5	0.7 [4.2]	0.5 [3.0]	1.2 [7.2]	10.1 [2.9]	10.3 [2.9]	10.0 [2.9]
50	2.4	0.6 [2.7]	0.4 [1.9]	1.0 [4.6]	15.5 [5.0]	15.7 [5.1]	15.4 [5.0]
60	3.1	1.1 [4.2]	0.8 [3.0]	1.8 [7.3]	9.8 [3.5]	10.0 [3.5]	9.7 [3.5]
70	1.2	0.6 [2.0]	0.4 [1.4]	1.0 [3.4]	21.6 [8.2]	21.9 [8.3]	21.5 [8.1]
80	0.9	0.5 [1.7]	0.4 [1.2]	0.9 [2.9]	26.0 [10.4]	26.4 [10.5]	25.8 [10.3]
90	2.6	2.0 [6.0]	1.5 [4.3]	3.5 [10.3]	7.7 [3.2]	7.8 [3.2]	7.6 [3.1]
100	1.4	1.4 [3.8]	1.0 [2.8]	2.4 [6.6]	12.6 [5.4]	12.8 [5.4]	12.5 [5.3]
110	0.9	1.0 [2.7]	0.7 [1.9]	1.7 [4.6]	18.9 [8.2]	19.2 [8.3]	18.8 [8.2]
120	1.1	1.6 [4.0]	1.1 [2.9]	2.7 [6.9]	13.3 [5.9]	13.5 [6.0]	13.2 [5.9]
130	1.8	3.0 [7.3]	2.1 [5.3]	5.1 [12.6]	7.6 [3.4]	7.8 [3.5]	7.6 [3.4]
140	1.9	3.5 [8.4]	2.5 [6.0]	6.0 [14.3]	7.0 [3.2]	7.1 [3.3]	7.0 [3.2]
150	1.6	3.5 [8.2]	2.5 [5.9]	6.0 [14.1]	7.5 [3.5]	7.6 [3.5]	7.4 [3.4]
160	1.1	2.7 [6.3]	2.0 [4.5]	4.7 [10.9]	10.2 [4.8]	10.4 [4.8]	10.1 [4.7]
170	0.6	1.7 [4.0]	1.3 [2.9]	3.0 [6.8]	17.0 [8.0]	17.2 [8.1]	16.9 [7.9]
180	0.9	2.7 [6.1]	1.9 [4.4]	4.6 [10.4]	11.6 [5.5]	11.8 [5.6]	11.6 [5.4]
190	0.9	3.2 [7.1]	2.3 [5.1]	5.5 [12.2]	10.4 [4.9]	10.5 [5.0]	10.3 [4.9]
200	0.9	3.3 [7.3]	2.4 [5.2]	5.7 [12.5]	10.6 [5.1]	10.8 [5.1]	10.5 [5.0]

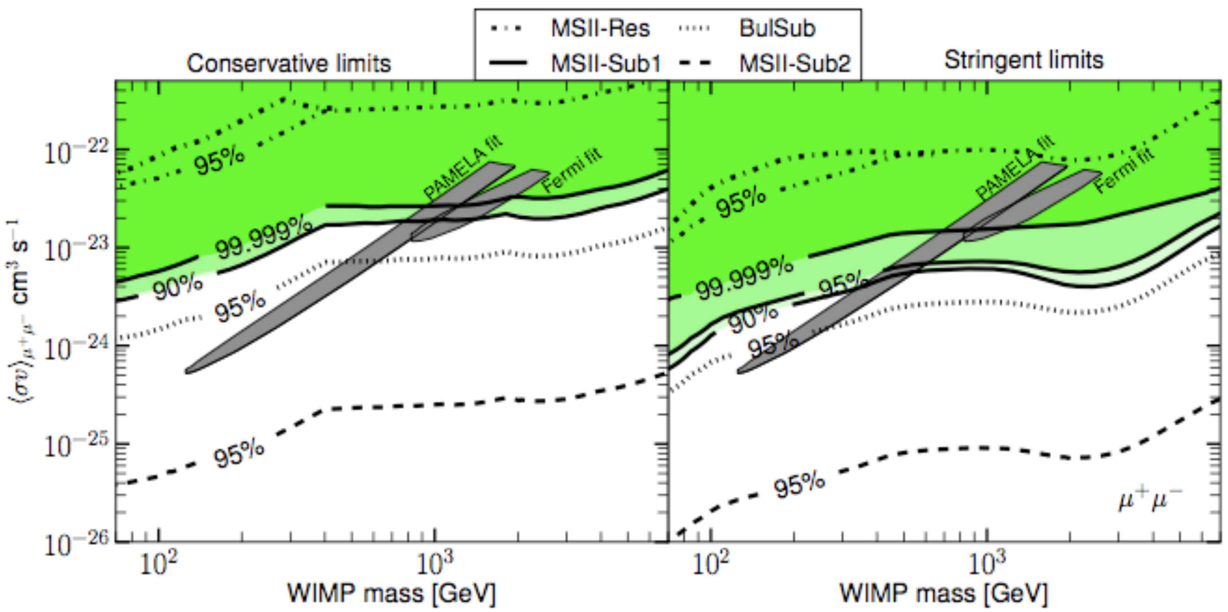
TABLE I: Flux, annihilation cross-section upper limits, and decay lifetime lower limits: γ-ray energies measured and corresponding 95% c.l. upper limits (CLUL) on fluxes, for $|b| > 10^\circ$ *plus* a $20^\circ \times 20^\circ$ square around the Galactic center. For each energy and flux limit, $\langle\sigma v\rangle_{\gamma\gamma}$ and $\langle\sigma v\rangle_{\gamma Z}$ upper limits, and $\tau_{\gamma\gamma}$ and $\tau_{\gamma Z}$ lower limits are given for three Galactic dark matter distributions (see text). The systematic error in the absolute energy of the LAT discussed in the text propagates to a $-20\% + 10\%$ systematic error on $\langle\sigma v\rangle_{\gamma\gamma}$, while for the decay lower limits the systematic error in the absolute energy of the LAT discussed in the text propagates to a $+10\% - 5\%$ systematic error on $\tau_{\gamma\gamma}$.

Constraints on 4 muons channel

Gamma ray constraints $0 \leq l \leq 360°,\ 10° \leq |b| \leq 90°$

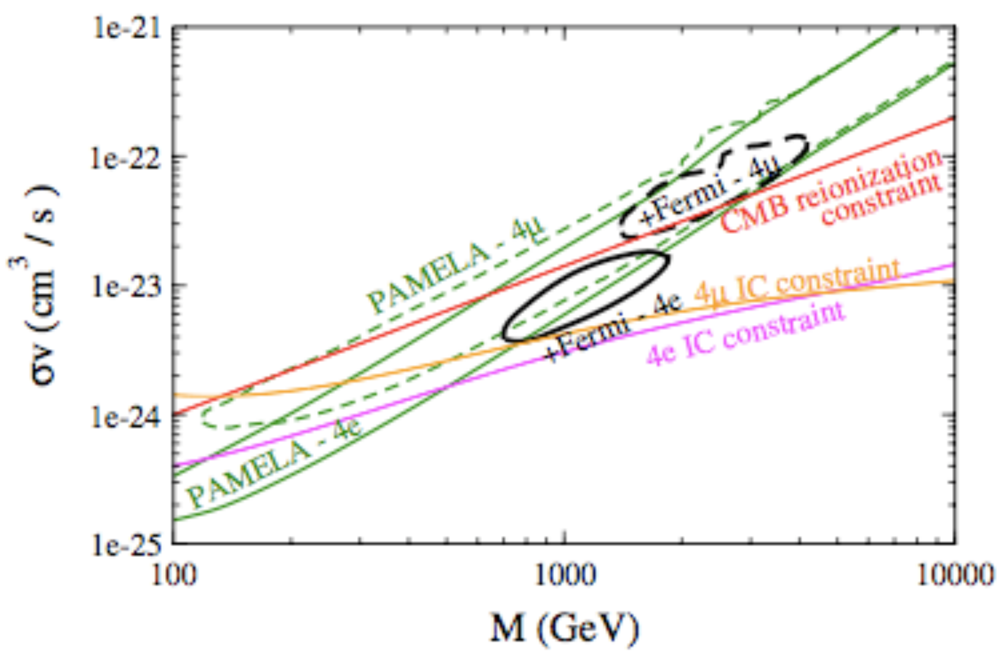
Extragalactic diffuse

Abdo et al., JCAP1004:014 (2010)



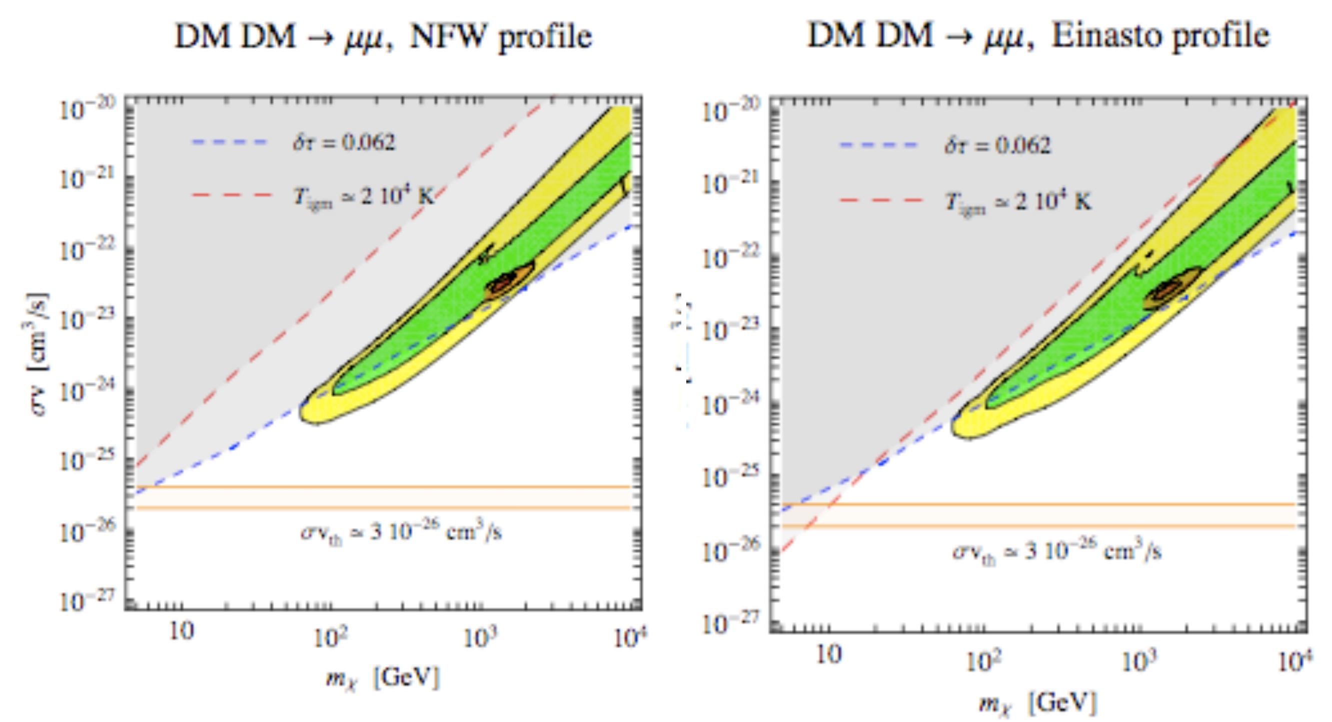
+ IC from ISRF in the Milky way

Cirelli, Cline, Phys.Rev.D82 (2010)



Reionization, heating

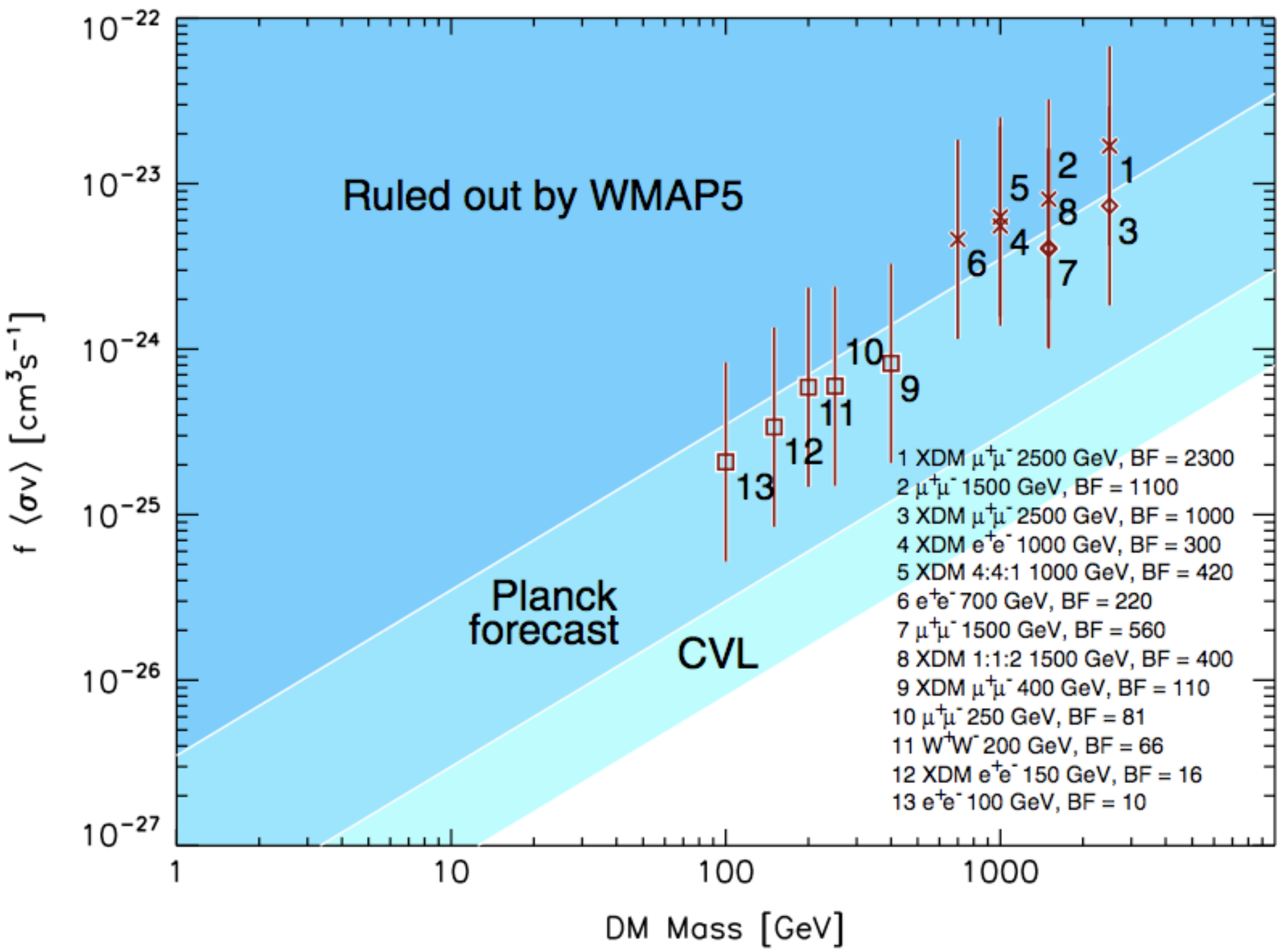
Cirelli, Iocco, Panci JCAP 0910:009 (2010)



Constraints on light ϕ

CMB

(Slatyer et al. Phys.Rev.D80 (2009); Galli et al, arXiv:1005.3008)



BBN -> photodissociation of light elements

Hisano, Kawasaki, Kohri, Moroi and Nakayama, Phys.Rev.D79 (2009); Kohri McDonald and Sahu, Phys.Rev.D81 (201

^{3}He/D constraints

$$\mathrm{DM} + \mathrm{DM} \rightarrow e^+ + e^-$$

$$\langle \sigma v \rangle < 7.0 \times 10^{-24}\ \mathrm{cm}^3\ \mathrm{s}^{-1} \left(\frac{E_{\mathrm{vis}}}{2m_{\mathrm{DM}}}\right)^{-1} \left(\frac{m_{\mathrm{DM}}}{1\ \mathrm{TeV}}\right).$$

$$\mathrm{DM} + \mathrm{DM} \rightarrow \mu^+ + \mu^-$$

$$\lambda_\chi \lesssim 0.05 \times \left(\frac{M_\chi}{\mathrm{GeV}}\right)^{3/4} \left(\frac{E_{\mathrm{vis}}/M_\chi}{0.7}\right)^{-1/4}$$

C.A., F.X. Josse-Michaux and N. Sahu Phys.Lett.B691 (2010)

Radio constraints come from the GC, important for cuspy profiles

(Crocker, Bell, Balazs and Jones, Phys.Rev.D81 (2010); Bertone, Cirelli, Strumia and Taoso, JCAP0903:009 (2009))

Scalar model

C.A., F.X. Josse-Michaux and N. Sahu, Phys.Rev.D82 (2010)

$$S_e \lesssim 480 \times \left(\frac{M_S}{1\ \mathrm{TeV}}\right).$$

$$\langle S_e \rangle \gtrsim 1000 \times \left(\frac{M_S}{1\ \mathrm{TeV}}\right)^{1.85}.$$

$$\langle S_e \rangle \lesssim 1800 \times \left(\frac{M_S}{1\ \mathrm{TeV}}\right)^{1.95}.$$

Higgs mixing for light ϕ

In the basis (h, ϕ) the Higgs mixing matrix is:

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda_H v^2 & f_{H\phi} u v \\ f_{H\phi} u v & 2\lambda_\phi u^2 \end{pmatrix}.$$

For small Higgs portal coupling:

$$\theta_m \sim -\frac{f_{H\phi} u v}{2(\lambda_H v^2 - \lambda_\phi u^2)} \ll 1.$$

$$h_1 \sim h + \theta_m \phi$$ mainly SM Higgs

$$h_2 \sim \phi - \theta_m h$$ mainly hidden scalar boson