Aspects of Higgs portal DM models: light scalar singlet and intense γ-ray from hidden vector

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Higgs portal interaction

$$\mathcal{L} \ni \lambda\, H^\dagger H \phi^\dagger \phi$$ ⇐ where ϕ is

- the DM particle
- or a messenger between the SM and DM

⇓

simplest way to couple the SM to a hidden sector where DM could lay

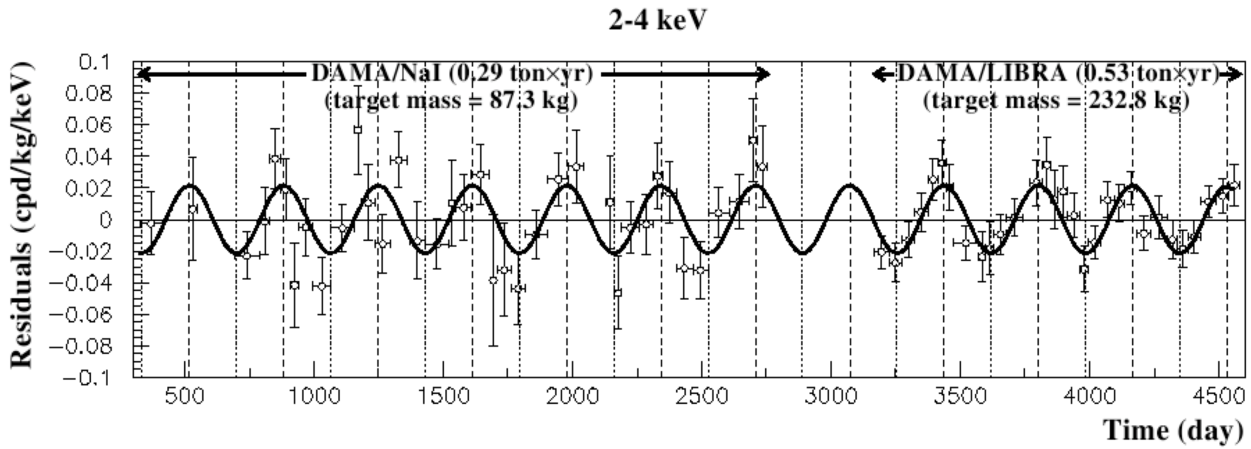
Part I.

DAMA and/or CoGeNT: scalar DM??

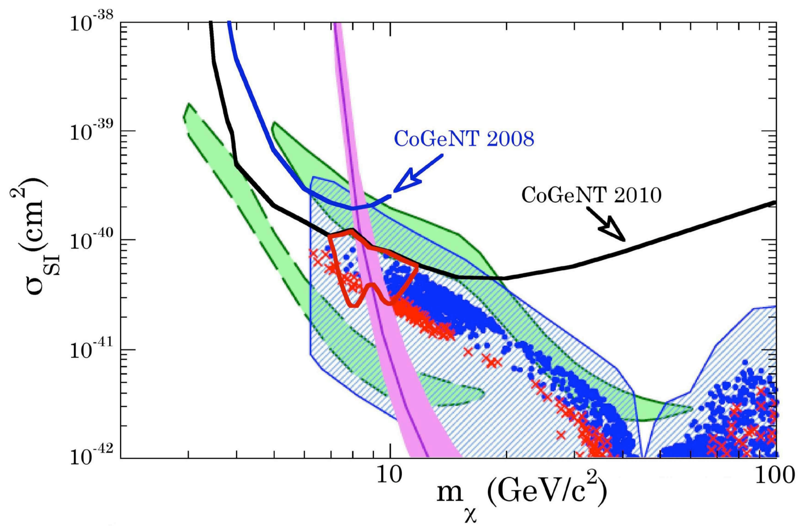
in collab. with S. Andreas, C. Arina, F.-S. Ling and M. Tytgat

DAMA and/or CoGeNT ???

DAMA:



CoGeNT:



⟹ could have nothing to do with DM but makes sense to look for simplest possible DM explanations of them

Possible DM annihilations to SM particles

if $m_{DM} \sim 10\,\mathrm{GeV}$: only $DM\,DM \to f\,\bar{f}$ $\quad (f = b, c, s, d, u, \tau, \mu, e, \nu_{e,\mu,\tau})$

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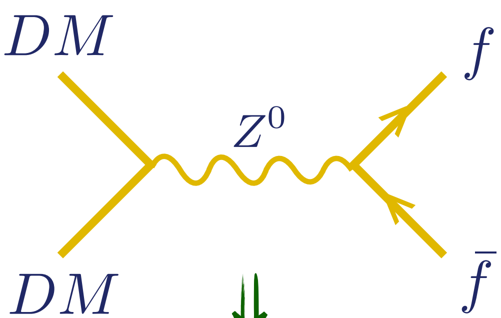
in 3 $\neq$ ways:

Z exchange:



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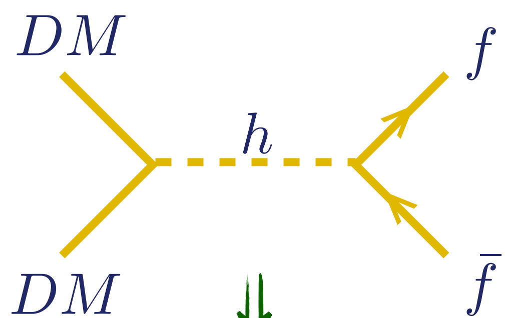
excluded by LEP
(invisible Z^0 width)

h exchange:



$\Downarrow$

to be analyzed

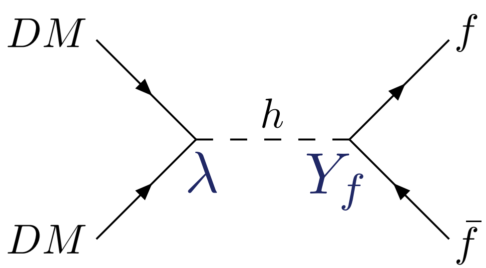
BSM particle exchange

e.g. squarks loops, ...

......

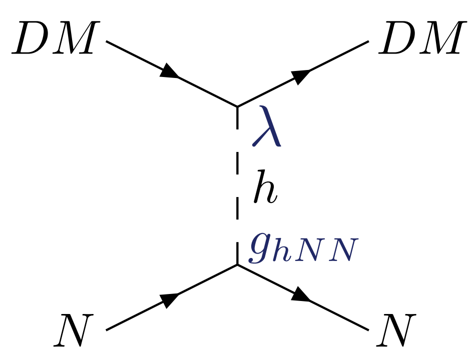
Predictivity of the Higgs exchange scenario

Annihilation cross section:



$$\sigma(DM\,DM \to f\,\bar{f})\,v_{rel} \propto \lambda^2 \frac{1}{(s-m_h^2)^2} Y_f^2 \cdot fct(m_{DM}) \sim \lambda^2 \frac{1}{m_h^4} Y_f^2 \cdot fct(m_{DM})$$

Cross section on Nucleon:



$$\sigma(DM\,N \to DM\,N) \propto \lambda^2 \frac{1}{(t-m_h^2)^2} g_{hNN}^2 \cdot fct'(m_{DM}) \sim \lambda^2 \frac{1}{m_h^4} g_{hNN}^2 \cdot fct'(m_{DM})$$

see also Burgess, Pospelov, ter Veldhuis 01'

⟹ the ratio of cross sections depends only on m_{DM}!

$$R \equiv \frac{\sigma(DM\,DM \to f\,\bar{f})\,v_{rel}}{\sigma(DM\,N \to DM\,N)} = fct''(m_{DM}, Y_f, g_{hNN})$$

⟹ if one fixes the Nucleon cross section to reproduce the DAMA and/or CoGeNT the relic density is fixed

The simplest DM model: a scalar singlet

DM= a real scalar singlet S:

Mc Donald 94', Burgess, Pospelov, ter Veldhuis 01', Patt, Wilczek 06'; Barger et al 08',...

$$\mathcal{L} \ni \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}\mu_S^2 S^2 - \frac{\lambda_S}{4} S^4 - \lambda_L H^\dagger H S^2$$

assuming a Z_2, $S \leftrightarrow -S$, symmetry for S stability

$$\lambda = \lambda_L v$$
$$m_S^2 = \mu_S^2 + \lambda_L v^2$$

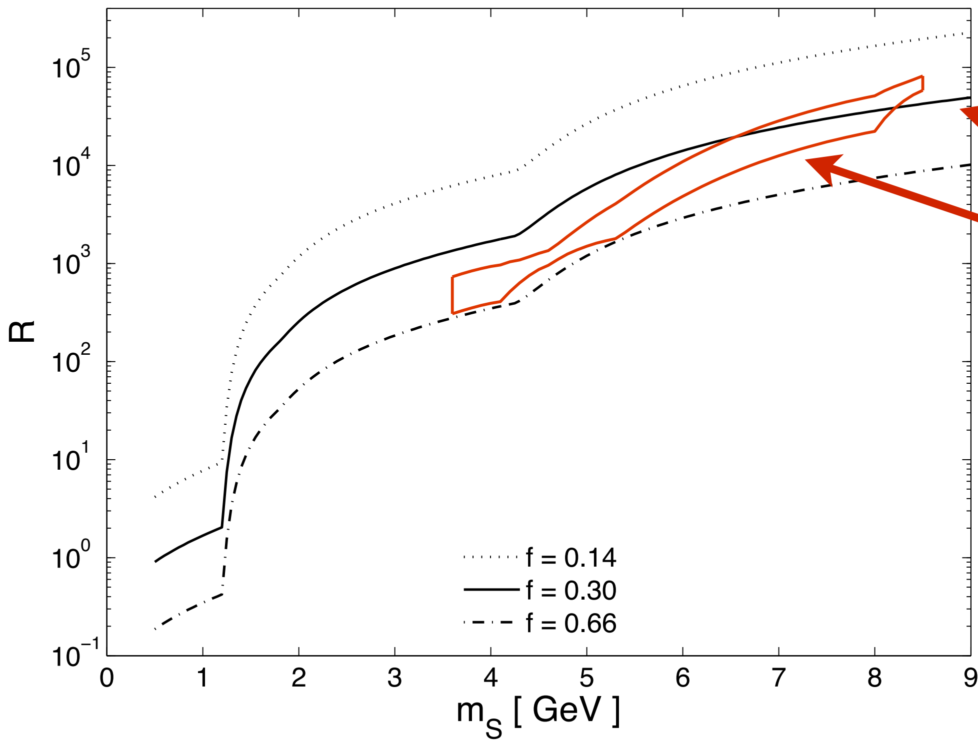
$$\sigma(SS \to \bar{f} f) v_{rel} = n_c \frac{\lambda_L^2}{\pi} \frac{m_f^2}{m_h^4 m_S^3} (m_S^2 - m_f^2)^{3/2}$$

$$\sigma(SN \to SN) = \frac{\lambda_L^2}{\pi} \frac{\mu_r^2}{m_h^4 m_S^2} f^2 m_N^2$$

$$R \equiv \sum_f \frac{\sigma(SS \to \bar{f} f) v_{rel}}{\sigma(SN \to SN)} = \sum_f \frac{n_c m_f^2}{f^2 m_N^2 \mu_r^2} \frac{(m_S^2 - m_f^2)^{3/2}}{m_S}$$

$$f m_N \equiv \langle N | \sum_q m_q \bar{q} q | N \rangle = g_{hNN} v$$

Results for the scalar singlet



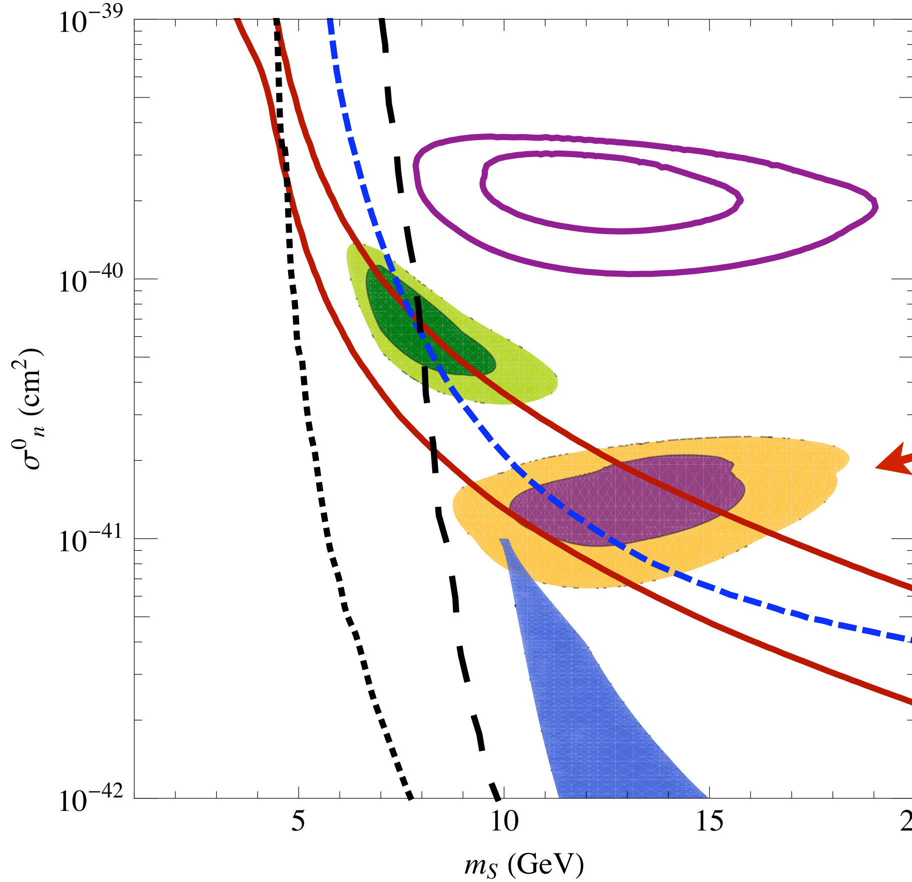
ratio predicted for f=0.3 central value

ratio required to match both DAMA and $0.094 < \Omega_{DM}h^2 < 0.129$

S. Andreas, T.H., M. Tytgat 08'

⟹ intriguing result $R \sim m_S^2, \ldots$

Results for the scalar singlet



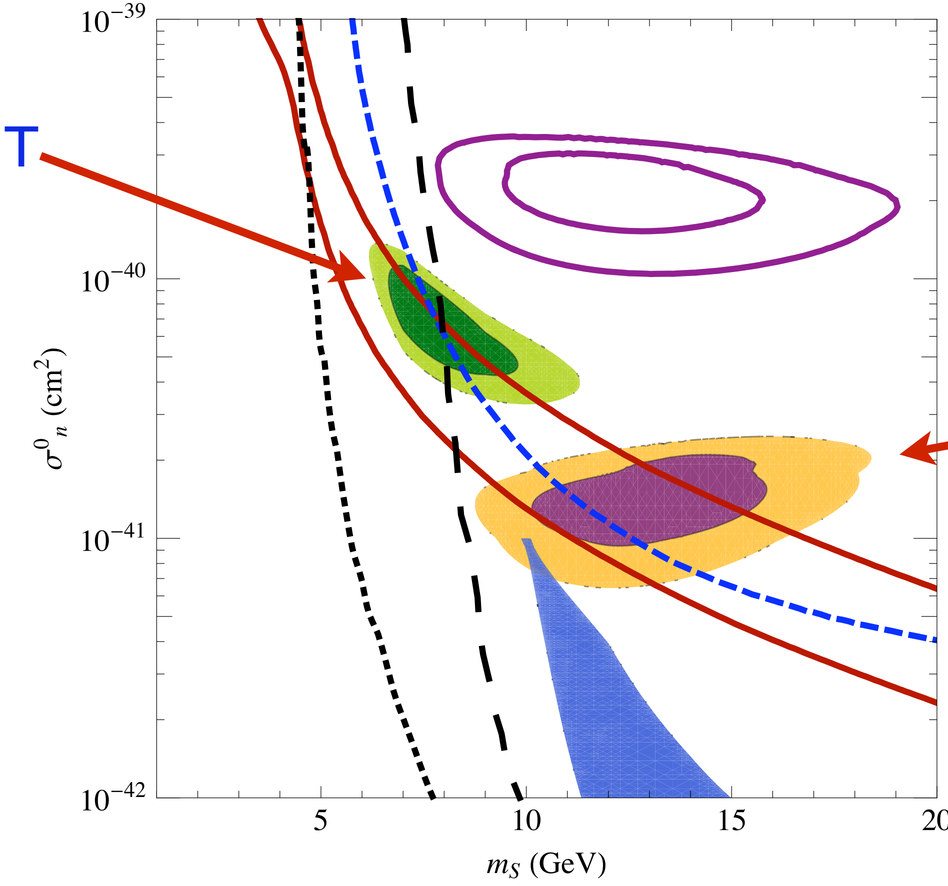
DAMA

value of Nucleon cross section obtained once one requires $0.094 < \Omega_{DM} h^2 < 0.129$ with $0.2 < f < 0.4$

S. Andreas, C. Arina, F.-S. Ling, T.H., M. Tytgat 10'

Results for the scalar singlet

CoGeNT



DAMA

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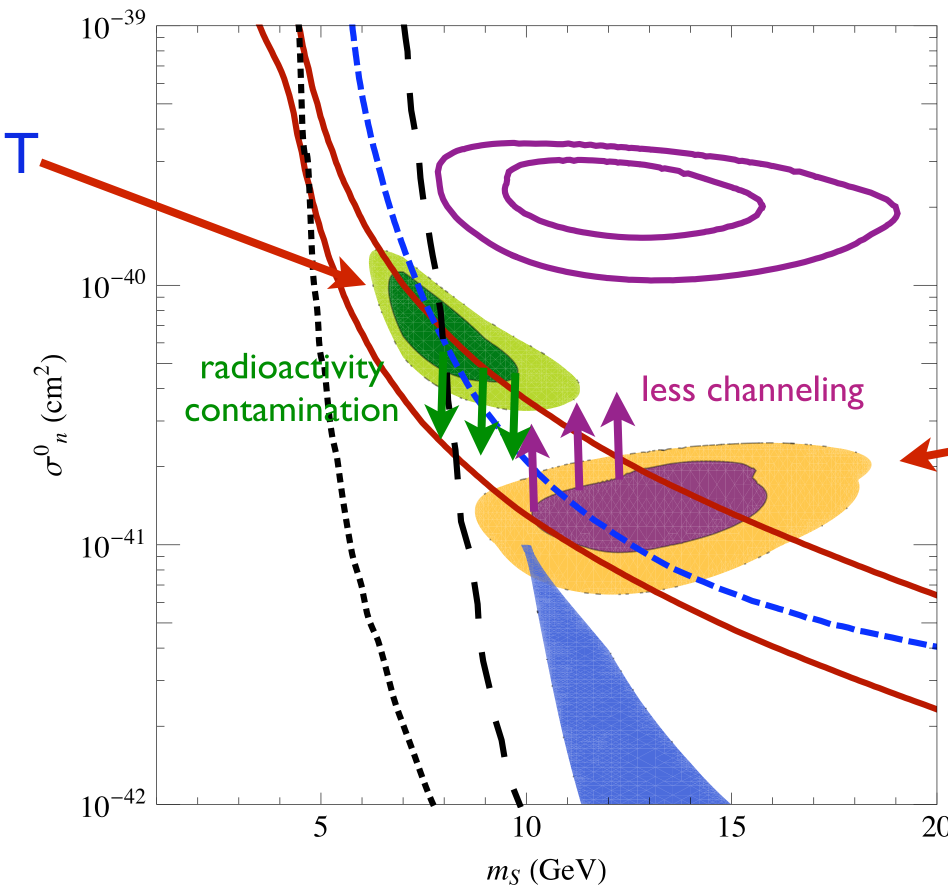
Results for the scalar singlet



CoGeNT

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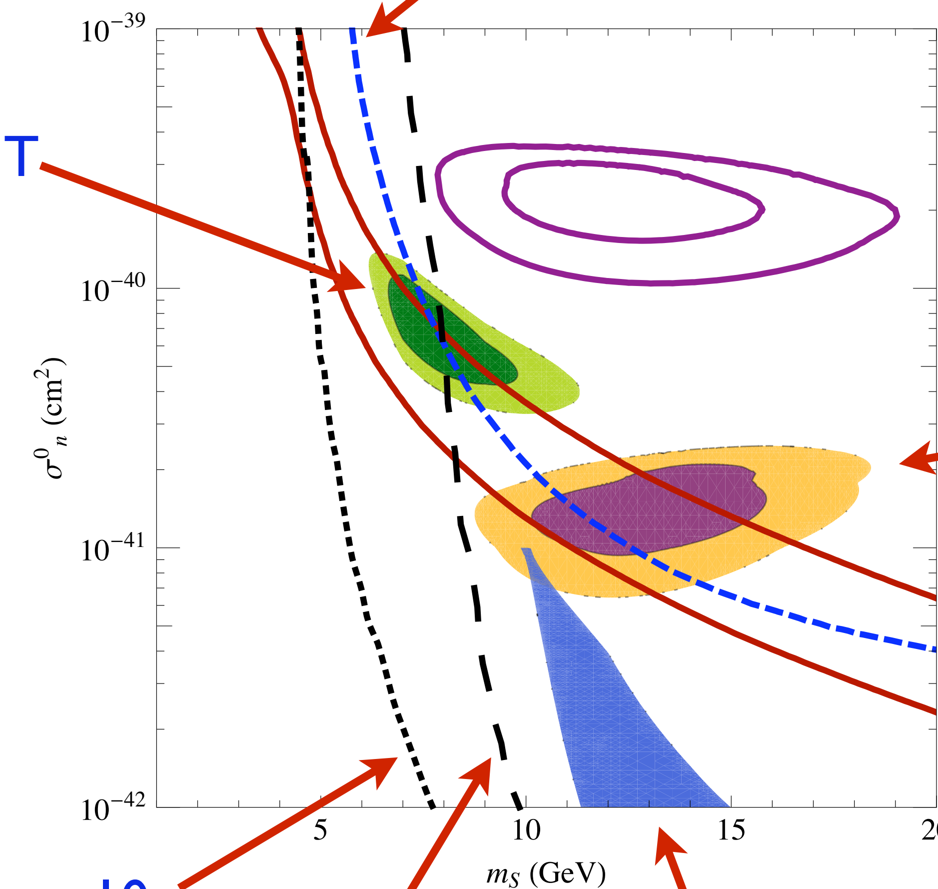
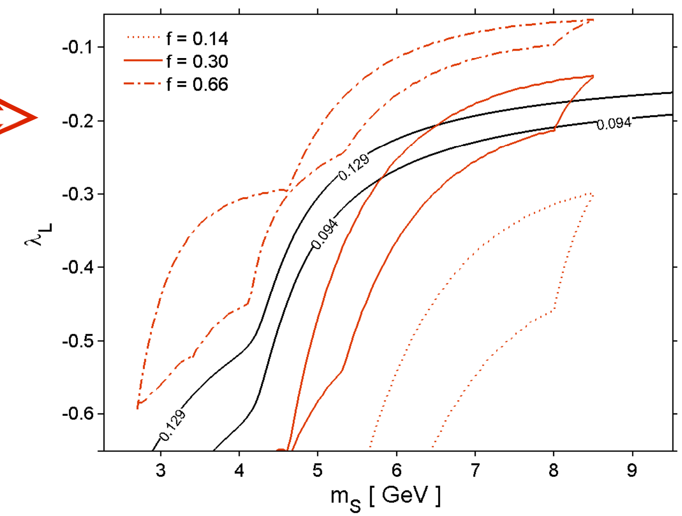


Issues

- Experimentally: -DAMA: channeling, ...
  -CoGeNT: radioactivity, ...
  -Xenon 10 and 100: scintillation efficiency, ...
  -CRESST?
- Theoretically: -value of f? $\Leftarrow$ Higgs exchange scenario requires 0.2 < f < 0.6
  -why a scalar around 5-10 GeV? $\Longleftarrow$ Ω_{DM}/Ω_B ?
  -fairly large value of λ_L is required:

$|\lambda_L| \sim 0.2 \Longrightarrow$



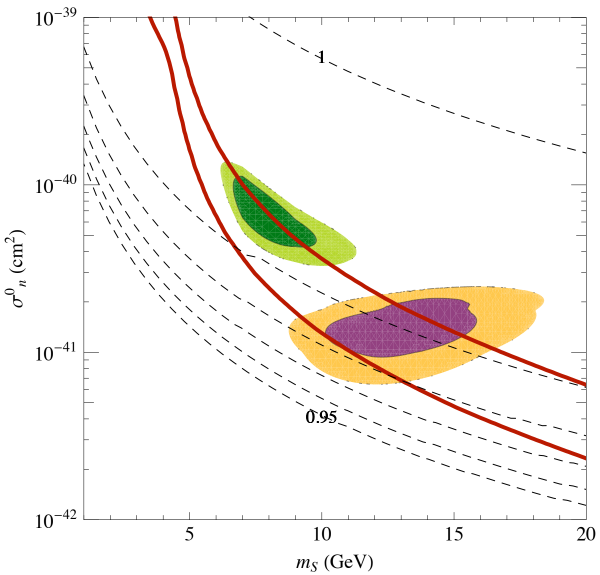
$\Longrightarrow m_S^2 = \mu_S^2 + \lambda_L v^2 \Longrightarrow$ tuning at the % level

$\mathcal{O}(10\,\mathrm{GeV})^2$ $\mathcal{O}(100\,\mathrm{GeV})^2$

not apparent in model independant analysis
such as in Fitzpatrick, Hooper, Zurek 10'

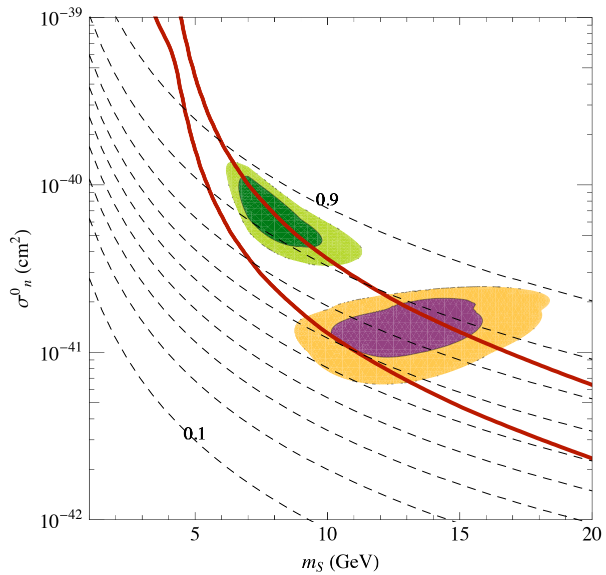
Consequences for Higgs invisible decay width

$m_H = 120\,\mathrm{GeV}$



$98\,\% < BR(H \to DMDM) < 99.5\,\%$

$m_H = 180\,\mathrm{GeV}$



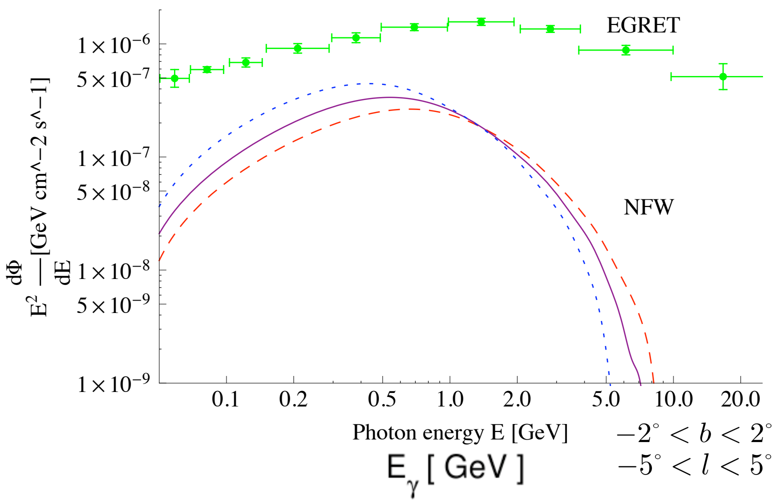
$60\,\% < BR(H \to DMDM) < 90\,\%$

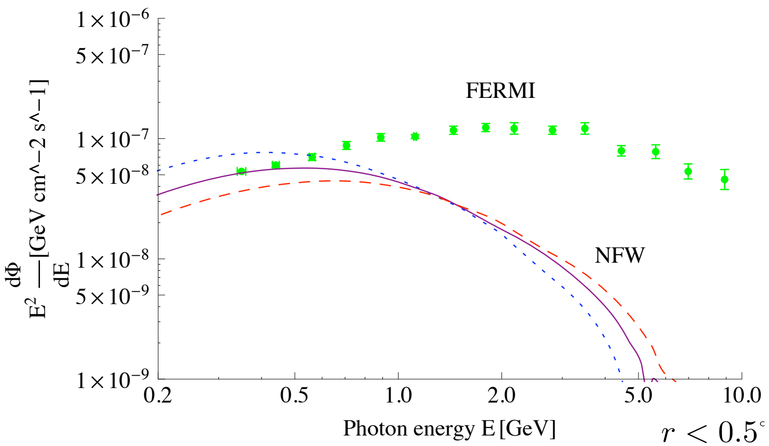
DAMA and CoGeNt lead to BR distinguishable at LHC

Indirect detection

γ rays from the galactic center:

Feng, Kumar, Strigari 08'
S. Andreas, T.H., M. Tytgat 08'

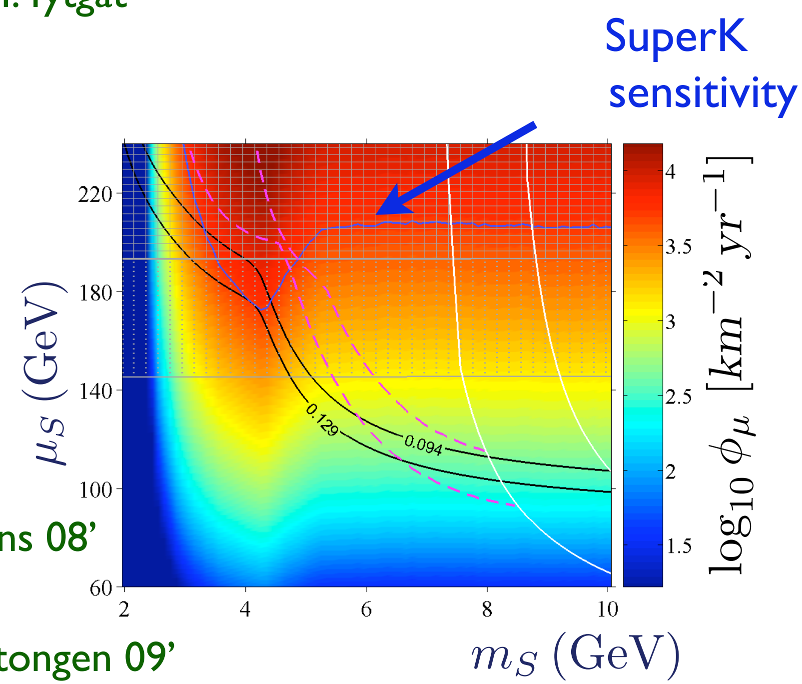




courtesy of M. Casier and M. Tytgat

Neutrino flux from DM annihilation in the Sun:

Savage, Gelmini, Gondolo, Freese 08';
Savage, Freese, Gondolo, Spolyar 09', ...



S. Andreas, M. Tytgat, Q. Swillens 08'

$\bar{p}$, De : Bottino, Donato, Fornengo, Scopel 08'; Nezri, Tytgat, Vertongen 09'

Higgs exchange scenario in other scalar models

the scalar DM particle doesn't necessarily need to be a weak singlet

also applies to inert doublet model ← DM = one neutral component H_0 of a second Higgs doublet

with other neutral component A_0 heavier than $\sim 80\,\mathrm{GeV}$ (LEP invis. Z decay width)

$Z \to H_0 A_0$

⇒ same predictions as for the singlet

Fermion DM with Higgs exchange

doesn't work!

Example: a Dirac fermion: $\mathcal{L} \ni \bar{\psi}(i\partial\!\!\!/ - m_0)\psi - \frac{Y_\psi}{\sqrt{2}}\bar{\psi}\psi h$

Annihilation: $\sigma(\bar{\psi}\psi \to \bar{f}f)v_{rel} = n_c \frac{Y_\psi^2}{16\pi} \frac{m_f^2 v_{rel}^2}{v^2 m_h^4} \frac{(m_\psi^2 - m_f^2)^{3/2}}{m_\psi}$ ⇐ extra $v_{rel}^2 \frac{m_{DM}^2}{v^2}$ suppression

↑ P-wave and helicity suppressed

Cross section on N: $\sigma(\psi N \to \psi N) = \frac{Y_\psi^2}{2\pi} \frac{\mu_r^2}{v^2 m_h^4} f^2 m_N^2$

⇒ much smaller predicted $R \equiv \frac{\sum_f \sigma(\bar{\psi}\psi \to \bar{f}f)v_{rel}}{\sigma(\psi N \to \psi N)} = \frac{\sum_f n_c m_f^2}{f^2 m_N^2 \mu_r^2} \frac{v_{rel}^2}{8} \frac{(m_\psi^2 - m_f^2)^{3/2}}{m_\psi}$

⇒ DAMA and/or CoGeNT can be reproduced but give a relic abundance way too large

Part II.

Intense γ-ray lines from hidden vector DM

in collab. with C. Arina, A. Ibarra and C. Weniger

Monochromatic γ-ray lines: a smoking gun for DM

$DM\,DM \to \gamma\gamma\,,\,\gamma Z$ annihilation leads to a monochromatic γ-ray line

(not expected in astrophysics background)

e.g. obtained at one loop level $\Rightarrow$ rather suppressed

$\Downarrow$

e.g. needs for large boost factor or a TeV DM mass

Boudjema, Semenov, Temes 05'; Bergstrom, Ullio, 97', 98';Bern, Gondolo, Perelstein 97'; Bergstrom, Bringmann, Eriksson, Gustafsson 04', 05'; Jackson, Servant, Shaughnessy, Tait, Taoso 09', ...
one tree level exception: Dudas, Mambrini, Pokorski, Romagnoni 09'

But what about a γ-ray line from DM decay?????

has been considered from gravitino decay through R-parity violation

Buchmuller, Covi, Hamagushi, Ibarra, Tran 07'; Ibarra, Tran 07'; Ishiwata, Matsumoto, Moroi 08'; Buchmuller, Ibarra, Shindou, Takayama, Tran 09'; Choi, Lopez-Fogliani, Munoz, de Austri 09'

A scenario for large γ-ray lines through DM decays

C. Arina, T.H., A. Ibarra, C. Weniger 09'

i.e. doesn't result from an ad-hoc symmetry
or from a gauge symmetry remnant subgroup

If DM stability results from an accidental symmetry (as proton in SM)

⇓

we expect higher dimensional operators destabilizing
the DM to be generated by higher scale physics

a dim-5 operator leads
to $\tau_{DM} << \tau_{Universe}$

⇑

even if $\Lambda \sim M_{Planck}$

but a dim-6 operator leads to a
γ-ray flux of order the expe-
rimental sensitivity if $\Lambda \sim M_{GUT}$

as for other cosmic rays:
Eichler; Nardi, Sannino, Strumia; Chen, Takahashi,
Yanagida; Arvanitaki, Dimopoulos et al.; Bae, Kyae;
Hamagushi, Shirai, Yanagida; ...

⇒ DM model based on accidental symmetry decaying to γ from dim-6 operator

Hidden vector DM

→ based on the existence of a accidental custodial symmetry:

- no possible dim-5 operators but dim-6 ones which all leads to a γ-ray line
- the stability can be "understood" only from the low-energy point of view as for the proton in the SM
- non-abelian global symmetry
- simple viable spin-1 DM model

Custodial symmetry $\Rightarrow$ DM stability

T.H. 08'

simplest example: a gauged SU(2) + a scalar doublet ϕ

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu a}F^{a}_{\mu\nu} + (D^{\mu}\phi)^{\dagger}(D_{\mu}\phi) - \mu_{\phi}^{2}\phi^{\dagger}\phi - \lambda_{\phi}(\phi^{\dagger}\phi)^{2}$$

$\Downarrow$

ϕ gets a vev v_ϕ

$$\phi = \begin{pmatrix} \phi^{+} \\ (\eta + i a_0 + v_\phi)/\sqrt{2} \end{pmatrix}$$

$\Rightarrow$ spectrum: - 3 degenerate massive gauge bosons V_i : $m_V = \frac{g_\phi v_\phi}{2}$

- one real scalar η: $m_\eta = \sqrt{2\lambda_\phi}\, v_\phi$

This lagrangian has a custodial symmetry $SU(2)_C$ or equivalently a $SO(3)_C$: $(V_1^{\mu}, V_2^{\mu}, V_3^{\mu}) =$ triplet and $\eta =$ singlet

$\Rightarrow$ the 3 V_i are stable! $\leftarrow$ $V_i \to \eta\eta, \ldots$ forbidden

Hidden sector through the Higgs portal

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Hidden\,Sector} + \mathcal{L}_{Higgs\,portal}$$

$SU(2)_{HS}$

$$\mathcal{L}_{Hidden\,Sector} = -\frac{1}{4} F^{\mu\nu a} F^{a}_{\mu\nu} + (D^{\mu}\phi)^{\dagger}(D_{\mu}\phi) - \mu_{\phi}^{2}\phi^{\dagger}\phi - \lambda_{\phi}(\phi^{\dagger}\phi)^{2}$$

$$\mathcal{L}_{Higgs\,portal} = -\lambda_{m}\phi^{\dagger}\phi H^{\dagger} H$$

$$\ni -\lambda_{m} v_{\phi}\, v\, h\, \eta$$ → $h - \eta$ mixing

⇓

doesn't spoil the stability of the V_i^{μ}

Dimension-6 operators breaking the custodial symmetry

C. Arina, T.H., A. Ibarra, C. Weniger 09'

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

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

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

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

all give 2-body decay to γh or $\gamma\eta$

examples of branching ratios:

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

operator A & B

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

operator 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

operator D

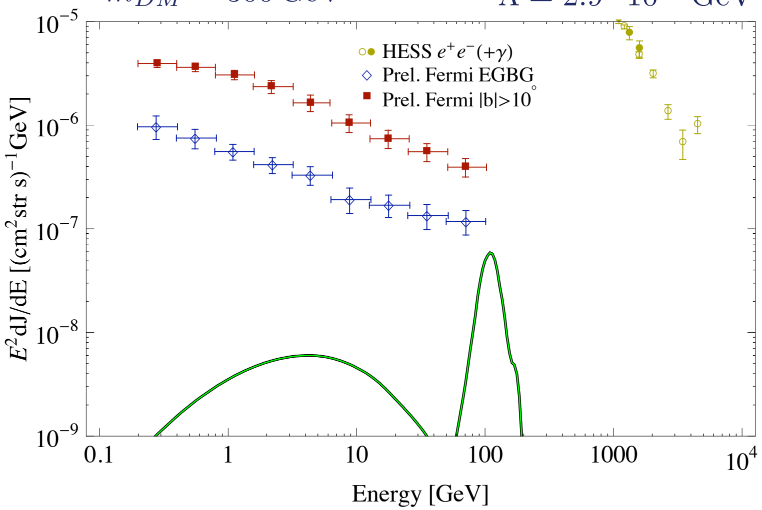
Benchmark	$Z\eta$	Zh	$\gamma\eta$	W^+W^-	$\nu\bar{\nu}$	e^+e^-	$u\bar{u}$	$d\bar{d}$
1	0.01	0.005	0.04	0.02	0.09	0.39	0.29	0.15
2	0.019	0.004	0.036	0.014	0.072	0.35	0.39	0.12
3	0.22	0.0002	0.73	0.0005	0.003	0.016	0.018	0.005

Flux of monochromatic γ-rays

$$0 \leq l \leq 360^\circ,\ 10^\circ \leq |b| \leq 90^\circ$$

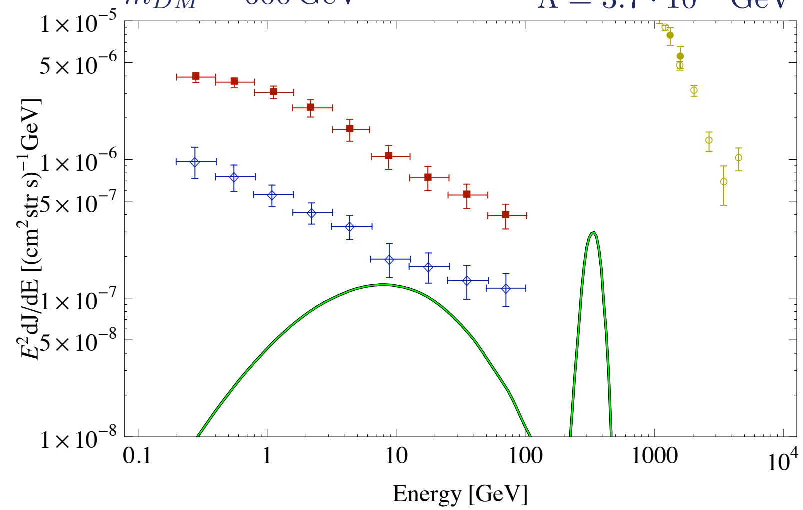
operator A & B

$m_{DM} = 300\,\mathrm{GeV}$ $\Lambda = 2.9 \cdot 10^{15}\,\mathrm{GeV}$



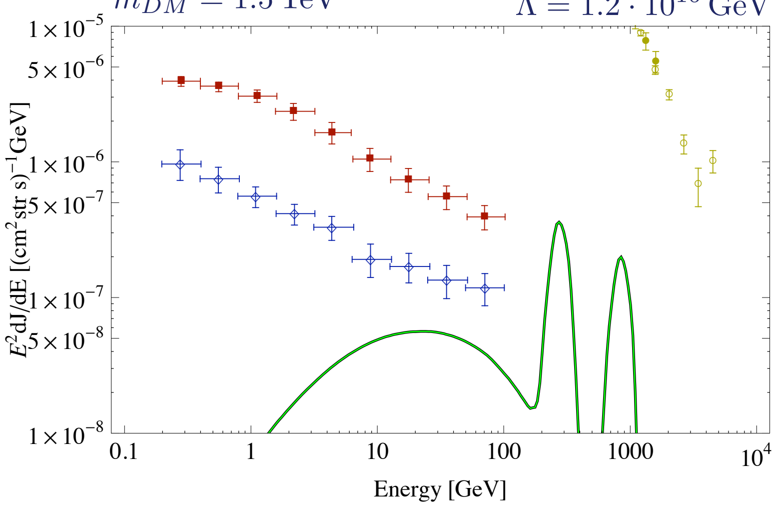
operator A & B

$m_{DM} = 600\,\mathrm{GeV}$ $\Lambda = 3.7 \cdot 10^{15}\,\mathrm{GeV}$ $\leftarrow \tau_{DM} = 1.6 \cdot 10^{27}\,\mathrm{sec}$



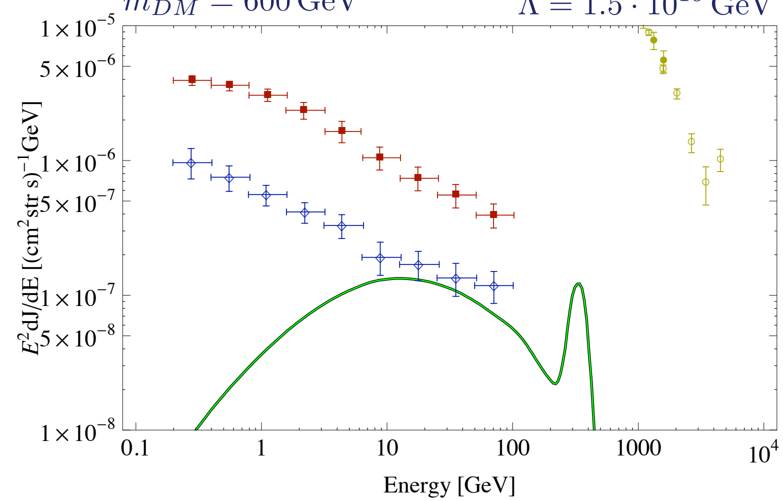
operator C

$m_{DM} = 1.5\,\mathrm{TeV}$ $\Lambda = 1.2 \cdot 10^{16}\,\mathrm{GeV}$



operator D

$m_{DM} = 600\,\mathrm{GeV}$ $\Lambda = 1.5 \cdot 10^{16}\,\mathrm{GeV}$



C. Arina, T.H., A. Ibarra, C. Weniger 09’

Backup

Relic density

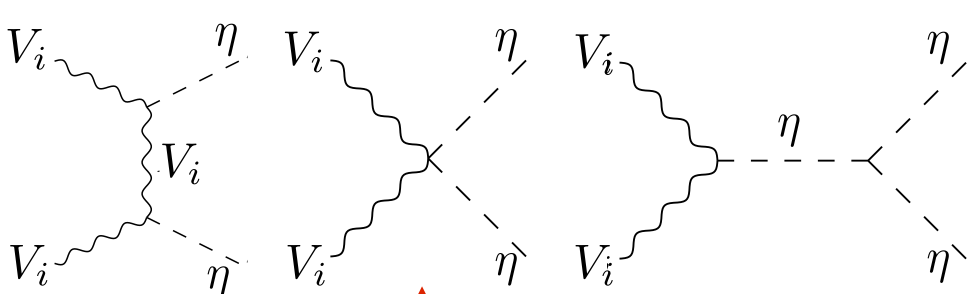
- $T \gtrsim m_V$: $V^{\mu}_{1,2,3}$ in thermal equilibrium with SM thermal bath

  η with h :due to λ_m coupling
  V_i with η :due to g_ϕ coupling

- $T < m_V$: $n_V^{eq.} \sim e^{-m_V/T}$ $\Rightarrow$ annihilation freeze out (WIMP)

to two real η:

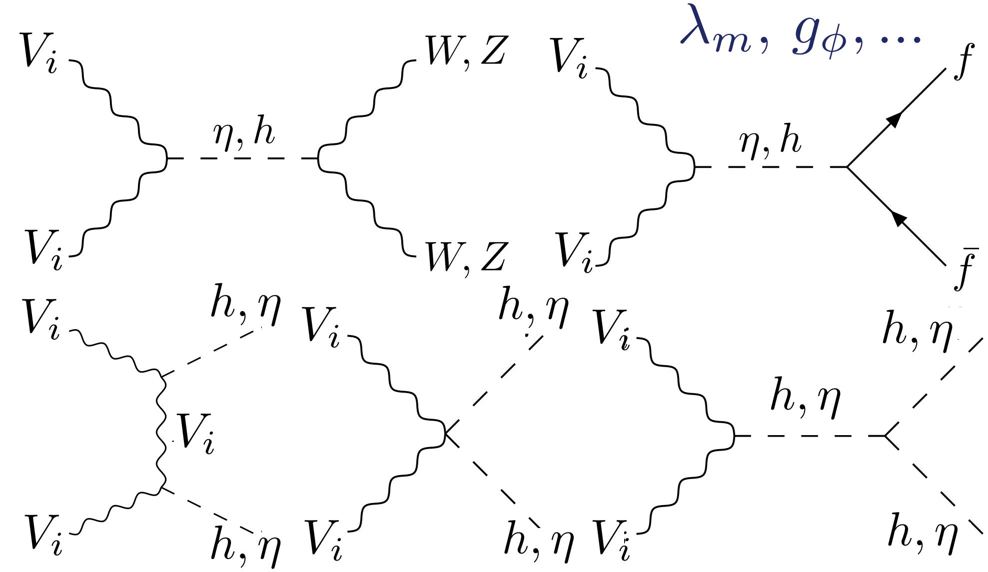
$g_\phi \; (+\lambda_\phi)$



with subsequent decay of η to SM particles via $h - \eta$ mixing

with at least one SM part. in final state:

$\lambda_m, \; g_\phi, \dots$



Relic density: additional new type of contribution

non abelian trilinear gauge couplings:

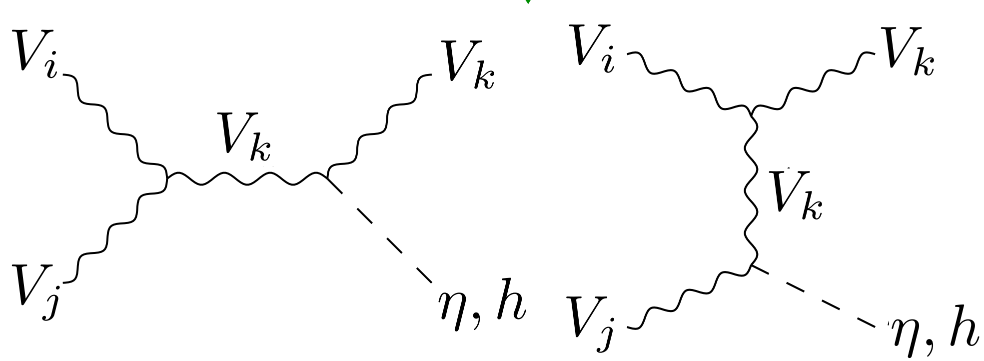
$$F^a_{\mu\nu} F^{\mu\nu a} \ni \varepsilon_{ijk} \partial_\mu A_{i\nu} (A^\mu_j A^\nu_k - A^\nu_j A^\mu_k)$$

do not lead to any V_i decay even if trilinear (carries 3 $\neq$ indices)

but induces two DM to one DM particle annihilation

$\Downarrow$

$\neq$ from the Z_2 case



$\Rightarrow$ no dramatic effect for the freeze out (same order as other diagrams)

Small Higgs portal regime

$\lambda_m \lesssim 10^{-3}$ ← (but larger than $\sim 10^{-7}$ to have thermalization with the SM bath)

$V_i V_i \to \eta\eta\,, V_i V_j \to V_k \eta$ dominant

depend only on $g_\phi\,, v_\phi, \lambda_\phi$ with $m_V = \dfrac{g_\phi v_\phi}{2}$, $m_\eta \simeq \sqrt{2\lambda_\phi}\, v_\phi$

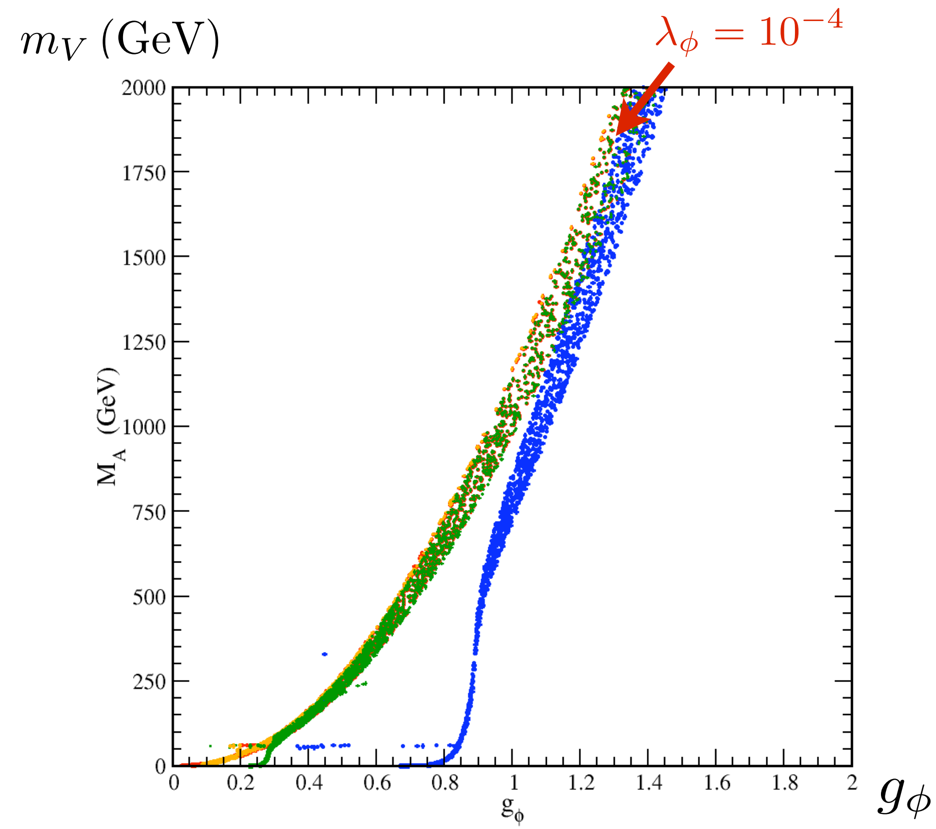
⇒ if λ_ϕ also small:

$$\sigma_{annih.} \sim \frac{g_\phi^4}{m_V^2} \sim \frac{g_\phi^2}{v_\phi^2}$$

⇓

$$m_V \propto g_\phi^2 \quad (\propto v_\phi^2)$$

⇒ $1\,\mathrm{MeV} \lesssim m_{DM} \lesssim 25\,\mathrm{TeV}$



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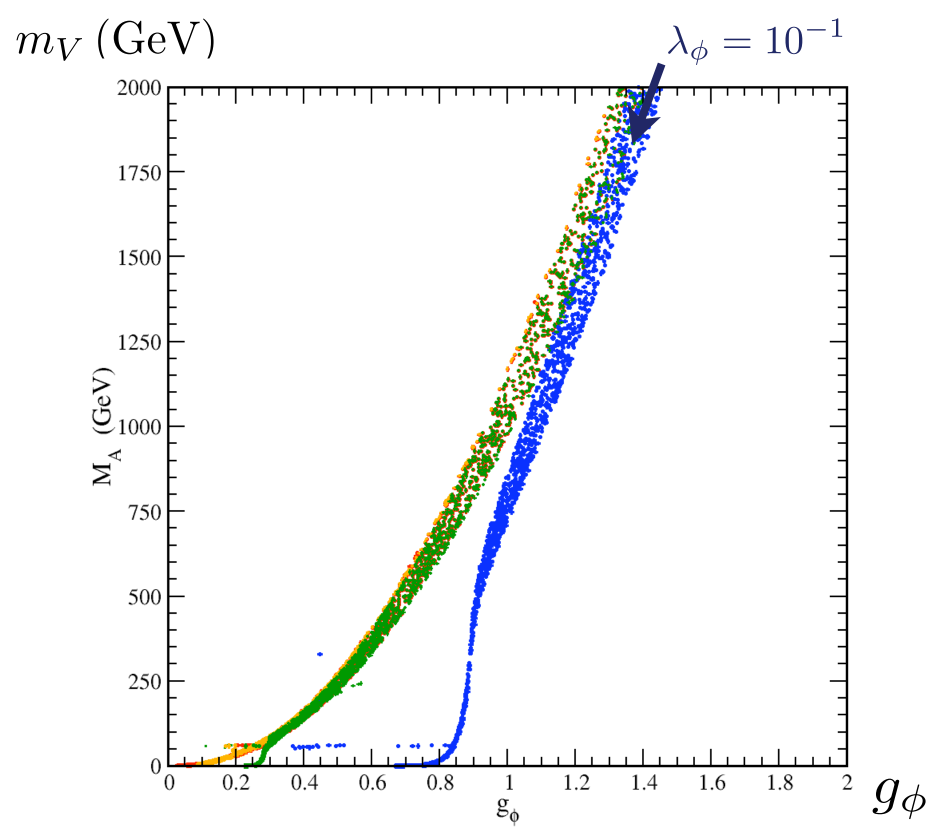
$V_i V_i \to \eta\eta \,, V_i V_j \to V_k \eta$ dominant

depend only on $g_\phi \,, v_\phi, \lambda_\phi$ with $m_V = \dfrac{g_\phi v_\phi}{2}$, $m_\eta \simeq \sqrt{2\lambda_\phi}\, v_\phi$

$\Rightarrow$ if λ_ϕ large:



Large Higgs portal regime

$\lambda_m \gtrsim 10^{-3}$ $\Longrightarrow$ large $\eta - h$ mixing $\Longrightarrow$ large hidden sector - SM mixing

can lead to the right Ω_{DM} even for maximal mixing

$\Downarrow$

production at LHC of η just as for the Higgs in the SM but with possibly a larger mass

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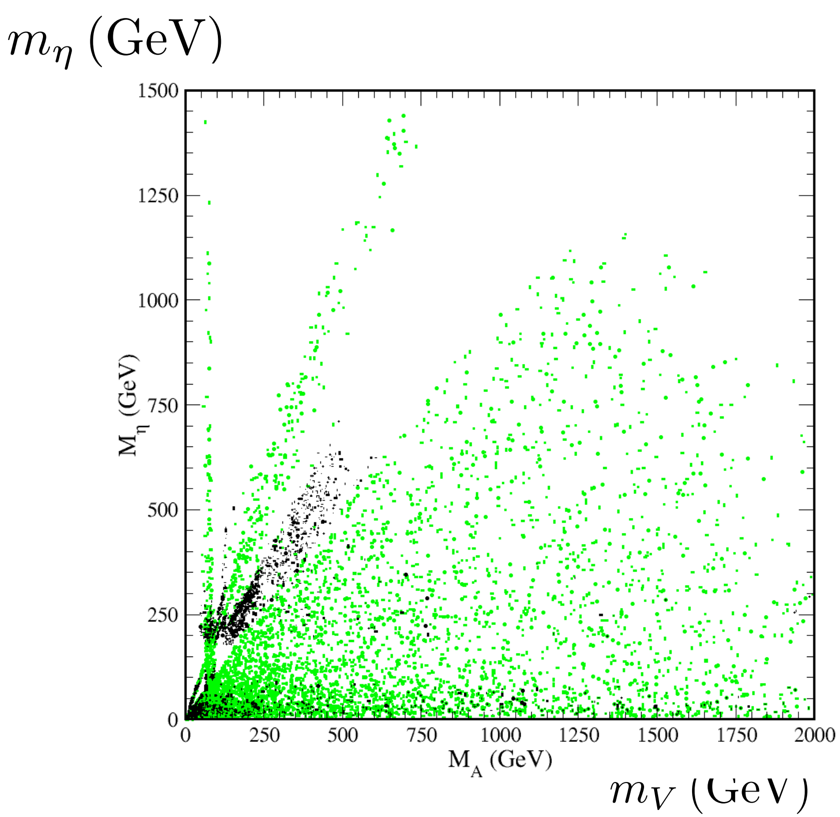


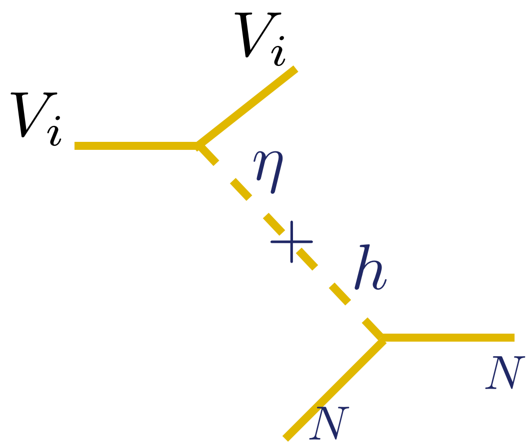
T parameter constraint:

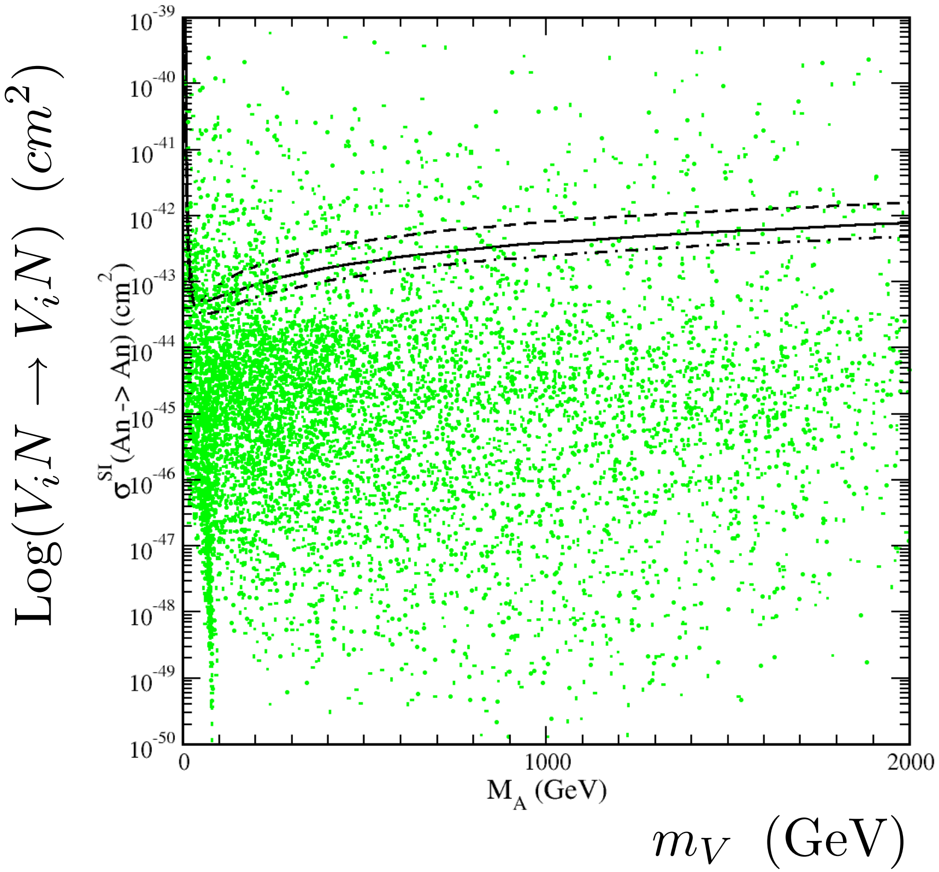
if $m_h = 120\,\mathrm{GeV}$ $\Rightarrow$ $m_\eta <\sim 240$ GeV (3σ)

or larger if non maximal mixing

if $m_\eta = m_h$ $\Rightarrow$ $m_h = m_\eta < 154$ GeV (3σ)

Hidden vector: direct detection





⇒ can saturate the experimental bound easily

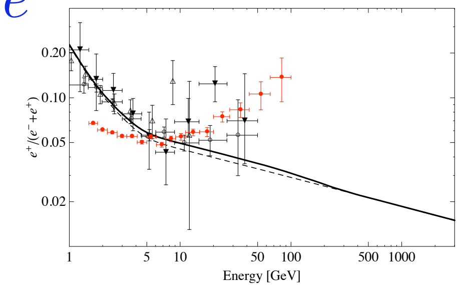
Hidden vector: cosmic ray fluxes

operator A & B

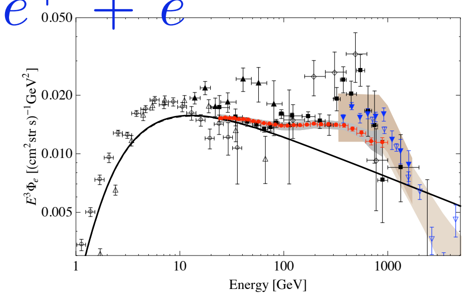
$m_{DM} = 300\,\mathrm{GeV}$

$\Lambda = 2.9 \cdot 10^{15}\,\mathrm{GeV}$

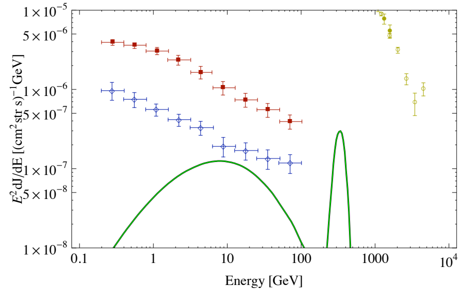
e^+



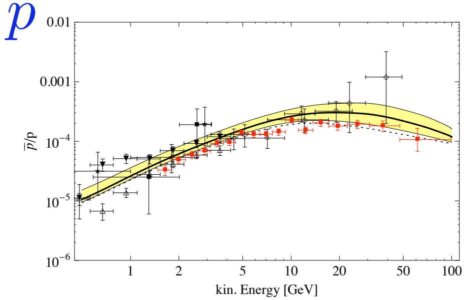
$e^+ + e^-$



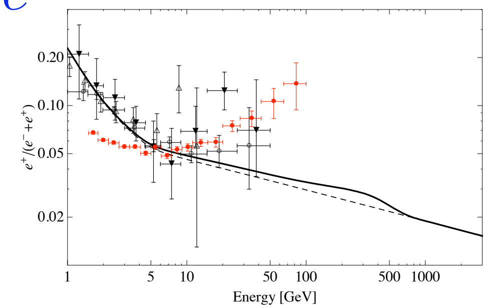
γ



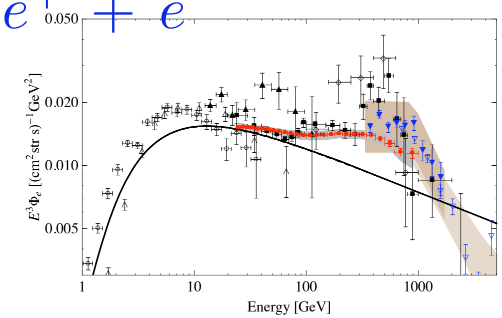
$\bar{p}$



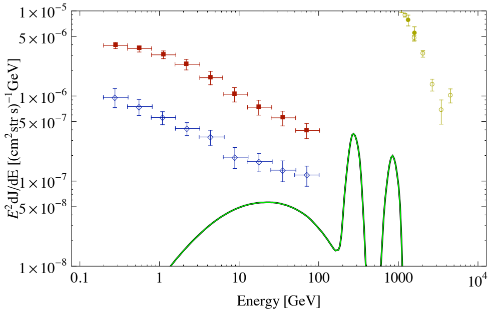
e^+



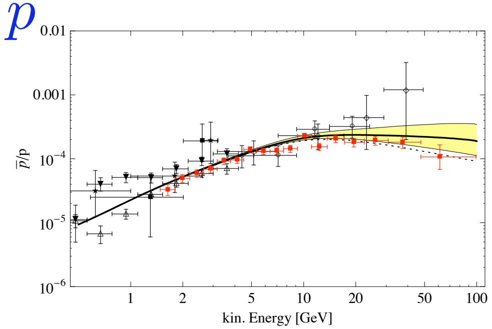
$e^+ + e^-$



γ



$\bar{p}$



operator C

$m_{DM} = 1.5\,\mathrm{TeV}$

$\Lambda = 1.2 \cdot 10^{16}\,\mathrm{GeV}$

Pamela: can we reproduce the positron spectrum?

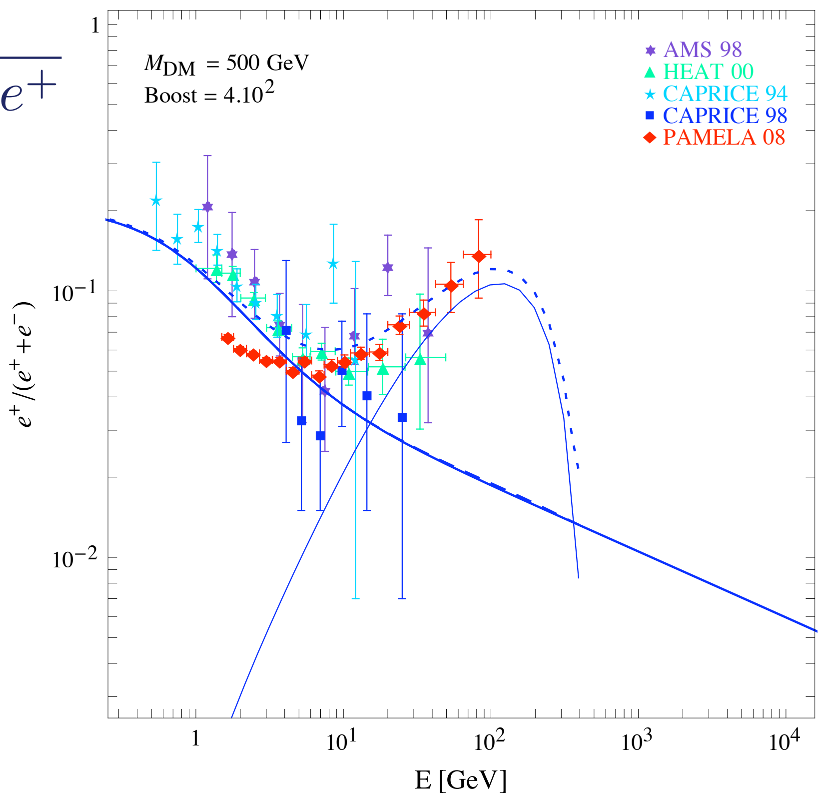
from annihilation: yes

$$m_V = 500\,\mathrm{GeV},\; m_\eta = 1\,\mathrm{GeV}$$

$$(V_i V_i \to \eta\eta \text{ dominant})\; \eta \to \mu^+\mu^-$$

as in Arkani-Hamed et al. light mediator scenario

$$\frac{e^+}{e^- + e^+}$$



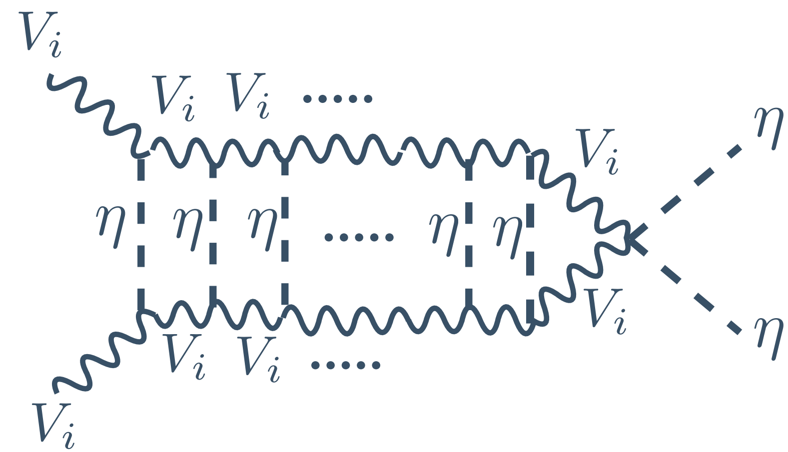
thanks to Gilles Vertongen

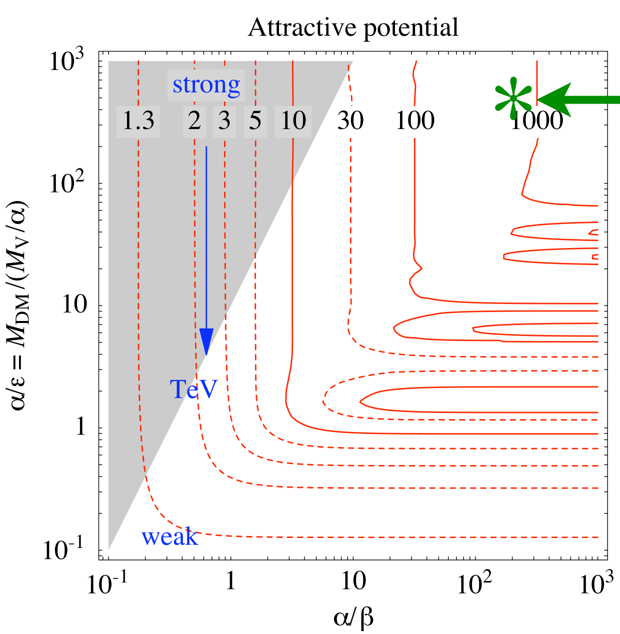
Pamela: can we get a large enough Sommerfeld boost?

η mediated between 2 V_i is attractive:

⇓

Sommerfeld boost:





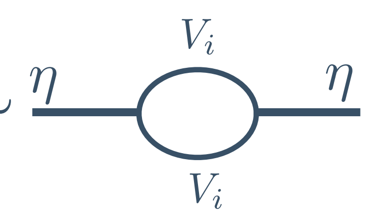
Cirelli, Strumia, Tamburini '07

where we are for example with: $m_V = 500\,\mathrm{GeV},\ m_\eta = 1\,\mathrm{GeV}$

(in agreement with Ω_{DM} which fixes the Sommerfeld coupling)

⇒ apparently the boost has just the right size

but m_η stability problem: $\delta m_\eta^2 \sim$



What about the non-perturbative regime of this model?

T.H., M. Tytgat, arXiv:0907.1007

→ SU(2)$_{\text{Hidden Sect.}}$ confines automatically if $\Lambda_{SU(2)} >> v_\phi$

$\Lambda_{SU(2)}$ ↓ dynamical scale

v_ϕ ↓ perturbative breaking scale

→ but the custodial symmetry remains exact in this case too

't Hooft '98

$\Rightarrow$ ϕ confines: boundstates are eigenstates of the custodial sym.:

- scalar state: $S \equiv \phi^\dagger \phi$ singlet of SO(3) expected the lightest
- "charged" vector state: $V_\mu^+ \equiv \phi^\dagger D_\mu \tilde{\phi}$
  $V_\mu^- \equiv \tilde{\phi}^\dagger D_\mu \phi$
- "neutral" vector state: $V_\mu^0 \equiv \frac{\phi^\dagger D_\mu \phi - \tilde{\phi}^\dagger D_\mu \tilde{\phi}}{\sqrt{2}}$

} SO(3) triplet $\Downarrow$ stable DM candidates!

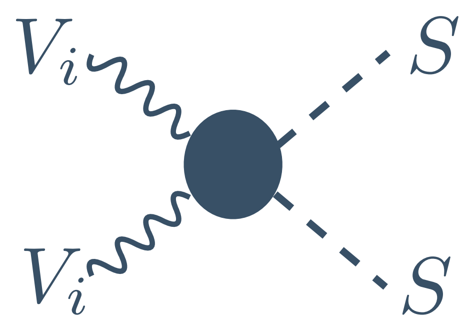
Relic density in the confined regime

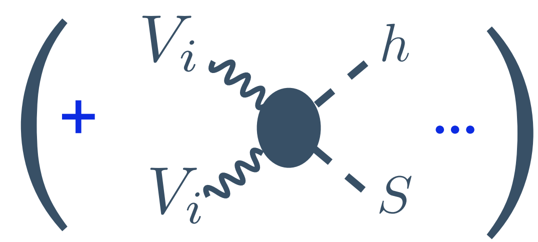
→ strongly interactive massive particle (SIMP)

→ annihilation cross section cannot be calculated perturbatively

⇓

expected dominant channel:





→ if $S-h$ mixing is large (for large λ_m)

⇓

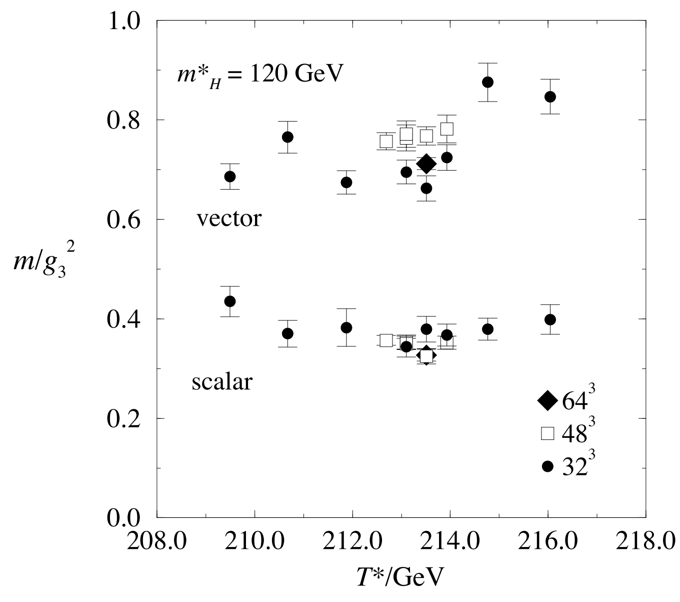
$A = 10-50$

$$\sigma_{annih.} \sim \frac{A}{\Lambda^2_{SU(2)}} \Rightarrow m_{DM} \simeq 20-120\,\mathrm{TeV}$$

$\Rightarrow$ confining non-abelian hidden sector coupled to the SM through the Higgs portal: perfectly viable DM candidate

Expected spectrum (in a similar case)

vector states e.g. expected heavier than scalar ones:



Kajantie, Laine. Rummukainen, Shaposhnikov ‘96

Possible effects on Electroweak Symmetry Breaking

→ contribution of the vev of the hidden scalar to the Higgs mass term:

$$\mathcal{L}_{Higgs\,portal} = -\lambda_m \phi^\dagger \phi H^\dagger H$$

$$\ni -\lambda_m v_\phi^2 H^\dagger H$$

⇓

gives a contribution to the Higgs vev: $v^2 \propto \frac{\lambda_m}{\lambda_H} v_\phi^2 \propto m_{DM}^2$

⇓

gives a hint for the m_{DM} versus v WIMP coincidence

see also T.H, M. Tytgat, arXiv 0707.0633, (PLB 659)