Phenomenological aspects of the dark matter stability origin

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03/06/2011

DM is astonishingly stable!

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

$\tau_{DM} \gtrsim 10^{26}\,\mathrm{sec}$ ⇐ in most models not to produce $e^+,\ \bar{p},\ \gamma,\ \ldots$ fluxes larger than observed

in many models: stability assumed by hand

⇓

e.g. ad hoc Z_2 symmetry ...

⇒ origin of the exceptional DM stability????

determines the basic DM model structure with specific phenomenology

Examples of specific phenomenology

deriving from

DM stabilization mechanisms

DM stability ⟹ long range forces??

DM stable as for the e^-: lightest charged particle under a unbroken gauged U(1)

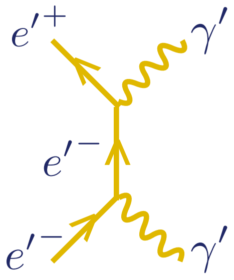
the simple adjunction of a new QED structure for a single fermion gives a viable DM candidate!!

Ackerman, Buckley, Carroll, Kamionkowski 08'; Feng, Tu, Yu 08'; Feng, Kaplinghat, Tu, Yu 09'
see also Foot at al. 06'-10'

$$\mathcal{L} = \mathcal{L}_{SM} + \underline{\mathcal{L}_{QED'}}$$

$$\mathcal{L}_{QED'} = \overline{\psi}_{e'}(i\partial\!\!\!/ - e\,\underset{\underset{\gamma'}{\downarrow}}{A\!\!\!/_{\gamma'}} - m_{e'})\underset{\underset{e'^{\pm}}{\downarrow}}{\psi_{e'}}$$

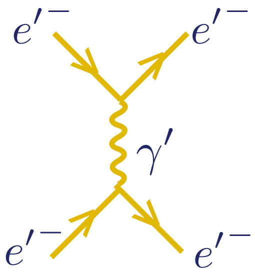
$e'^{\pm}$ ⟹ stable ⟹ $e'^{\pm}$ relic density:



α', $m_{e'}$, T'

⟹ long range force between charged DM $e'^{\pm}$

- galactic halo morphology modified by DM collisions through Rutherford scatter.
- more collisions in bullet cluster through Rutherford scattering
- damping of small scale structure due to lower kinetic decoupling



+ possible communication with SM through kinetic mixing

Lightest fermion of a secluded sector

e.g. assume:
- a new U(1) gauge interaction → a massive Z'
- a charged scalar ϕ breaking it → a Higgs boson
- a charged fermion ψ (vector) → a massive fermion ψ
- all SM fermions are neutral under U(1)

⇓

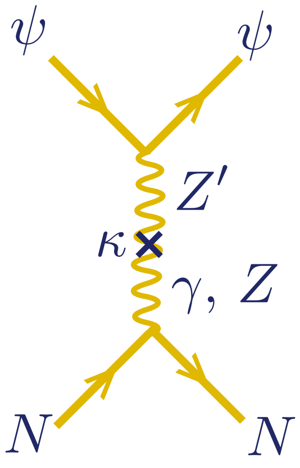
stable because lightest fermion of a secluded sector

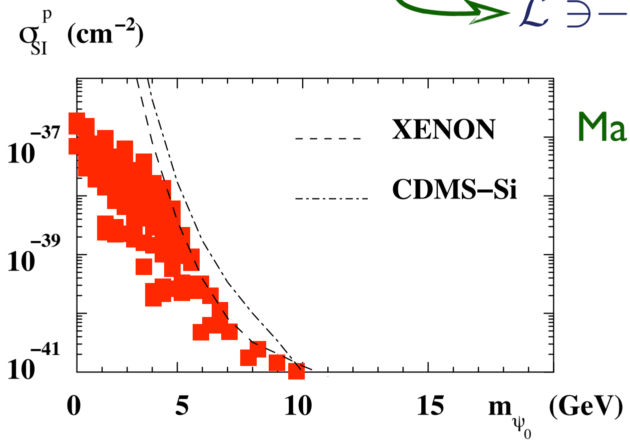
Pospelov, Ritz, Voloshin 07'
Gopalakrishna, Jung, Wells 08'
Gopalakrishna, Lee, Wells 08'

communication with SM through Higgs portal and kinetic mixing

$\mathcal{L} \ni - \lambda \, \phi^\dagger \phi \, H^\dagger H$

$\mathcal{L} \ni -\frac{1}{4} \, \kappa \, F^Y_{\mu\nu} \, F^{\mu\nu}_{QED'}$





Mambrini 10'

$\kappa \lesssim 10^{-(2-3)}$

can account for DAMA-CoGeNT
if $m_{DM} \sim m_{Z'}/2$ (resonance)

Remnant global subgroup of GUT: R-symmetry

Mohapatra 86', Martin 92'

$R_m = (-1)^{3(B-L)}$ ⇒ R-symmetry is a Z_2 subgroup of $U(1)_{B-L}$

⇓

a subgroup of $SO(10)$

⇒ if $U(1)_{B-L}$ (or $SO(10)$) is a gauge symmetry and is broken only by vev of fields with even B-L: R-symmetry remains as an exact symmetry

$10,\ 45,\ 54,\ 120,\ 126,\ 210,\ \ldots$

conserved by UV physics too

high energy explanation of R-symmetry ⇐ not experimentally testable (directly) but severely constrains the GUT model

Aulakh, Melfo, Rasin, Senjanovic 98'
Aulakh, Bajc, Melfo, Rasin, Senjanovic 01'
.....

DM stability in non-susy SO(10) setups

non-susy $U(1)_{B-L}$ (or $SO(10)$) gauge theories broken by only even B-L field vev also leaves a Z_2 symmetry

SM fermions are in the 16 of $SO(10)$ which is B-L odd

SM Higgs doublet is in the 10 of $SO(10)$ which is B-L even

the lightest component of an extra B-L odd scalar $SO(10)$ representation is stable

$16, \, 144, \, ...$

Kadastik, Kannike, Raidal 09'

the lightest component of an extra B-L even fermion $SO(10)$ representation is stable

$10, \, 45, \, 54, \, 120, \, 126, \, 210, \, ...$

Frigerio, TH 09'

45 or 54 fermion representation: DM is the neutral component of a fermion triplet $\Sigma^+, \, \Sigma^0, \, \Sigma^-$

can drive electroweak GUT unification

relic density requires $m_{DM} \simeq 2.7 \, \mathrm{TeV}$

Cirelli, Fornengo, Strumia 06'

stabilization mechanism "fixes" the DM mass

DM stability from accidental symmetry: DM decay

- if DM stable from accidental low energy symmetry we expect it to decay from new physics UV interactions as proton
  - intriguing coincidence: a GUT scale induced dim 6 operator

⇓

cosmic ray fluxes from DM decay
of order the observed ones

⇓

probe GUT scale physics??

Eichler; Nardi, Sannino, Strumia; Chen, Takahashi, Yanagida; Arvanitaki, Dimopoulos et al.; Bae, Kyae; Hamagushi, Shirai, Yanagida; Arina, TH, Ibarra, Weniger; ...

A smoking gun DM decay signal: intense γ-ray lines

TH 08'; TH, Tytgat 09'
Arina, TH, Ibarra, Weniger 10'

↪ if DM is a massive gauge boson, abelian or non abelian

$\Downarrow$

"Hidden vector": accidental custodial symmetry

$\Downarrow$

a gauged SU(2) + SSB from a scalar doublet ϕ

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

$\Downarrow$ ϕ gets a vev v_{ϕ}

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

$$m_{\eta} = \sqrt{2\lambda_{\phi}}\, v_{\phi}$$

3 massive gauge bosons V$_i$ + a real scalar η

↪ stable due to residual SU(2) custodial sym.

$V_i \rightarrow \eta\eta, \ldots$ forbidden:

$(V_1^{\mu}, V_2^{\mu}, V_3^{\mu}) =$ triplet

$\eta =$ singlet

+ communication with the SM through Higgs portal: $\mathcal{L}_{Higgs\,portal} = -\lambda_m \phi^{\dagger}\phi H^{\dagger} H$

↪ relic density, direct detection, ...

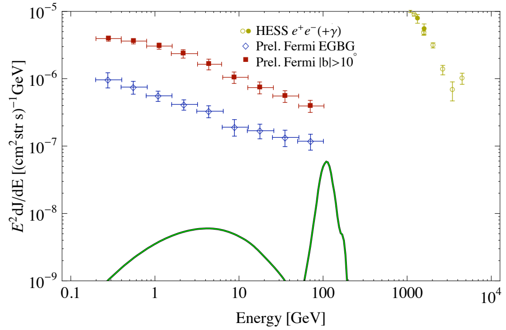
A smoking gun DM decay signal: intense γ-ray lines

Hidden vector: no reason that the custodial sym. not violated in the UV $\Rightarrow$ dim 6 operators:

$$\begin{array}{ll}
\text{(A)} & \frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\phi\;\mathcal{D}_\mu H^\dagger H \\
\text{(B)} & \frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\phi\;H^\dagger\mathcal{D}_\mu H \\
\text{(C)} & \frac{1}{\Lambda^2}\,\mathcal{D}_\mu\phi^\dagger\mathcal{D}_\nu\phi\;F^{\mu\nu Y} \\
\text{(D)} & \frac{1}{\Lambda^2}\,\phi^\dagger F^a_{\mu\nu}\frac{\tau^a}{2}\phi F^{\mu\nu Y}
\end{array}$$

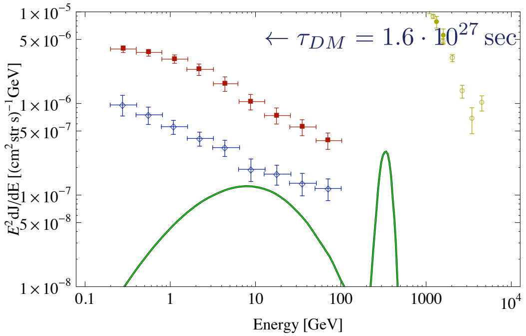
operator A & B

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



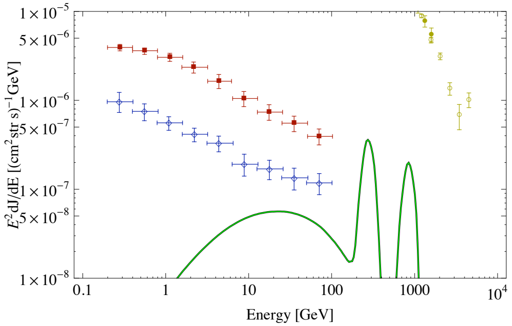
operator A & B

$m_{DM} = 600\,\mathrm{GeV}\;\Lambda = 3.7\cdot 10^{15}\,\mathrm{GeV}$



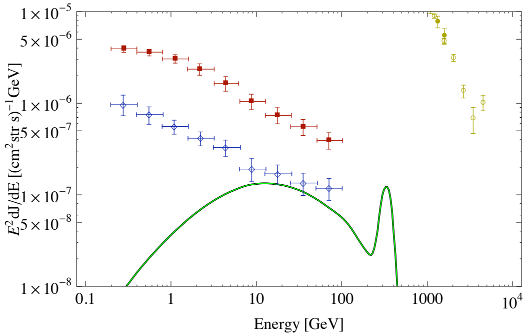
operator C

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



operator D

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



C. Arina, T.H., A. Ibarra, C. Weniger 10'

all give 2-body radiative decays

$\Downarrow$

monochromatic γ-rays

in particular off
the galactic plane!

DM smoking gun!!

(no astrophysical background!)

Annihilation: Bergstrom, Ullio, 97' 98';Bern, Gondolo, Perelstein 97'; Bergstrom, Bringmann, Eriksson, Gustafsson 04', 05'; Boudjema, Semenov, Temes 05'; Jackson, Servant, Shaughnessy, Tait, Taoso 09', ...

one tree level exception: Dudas, Mambrini, Pokorski, Romagnoni 09'

Decay: 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'

Dark Matter

as a

Pseudo Goldstone Boson

↪ stability: pseudo-Goldstone decay suppressed by large spontaneous breaking scale

↪ 2 well-known examples: - Axion

- DM Majoron

Cadamuro, Hasenkamp talks

The pseudo-Goldstone stabilization mechanism: Majoron case

Chikashige, Mohapatra, Peccei 81'

→ decay width suppressed by large seesaw scale

→ $U(1)_{B-L}$ breaking scale

- global $U(1)_{B-L}$ spontaneous breaking scale driven by L=2 scalar field ϕ

$$\mathcal{L} \ni -Y_{ij} N_{Ri} L_j H - \underline{\frac{1}{2} c_{ij} \phi N_{R_i} N_{R_j}}$$

$$\langle \phi \rangle \equiv f \;\Downarrow$$

$$-\frac{1}{2} M_{Nij}\, N_{R_i} N_{R_j}\, e^{i\theta/f} - \frac{1}{2}\, c_{ij}\, \phi'\, N_{R_i} N_{R_j}\, e^{i\theta/f}$$

Majoron

↓

$$\phi = (\phi' + f)\, e^{i\theta/f}$$

$$M_{Nij} = c_{ij} f$$

Akhmedov, Berezhiani, Senjanovic, Tao 93'

- additional explicit $U(1)_{B-L}$ breaking ⟶ Planck effects breaks the global sym. ⟶ massive Majoron

(or soft breaking terms, Gu, Ma, Sarkar 10')

⟹ DM massive Majoron stable because it couples only to SM through suppressed $\nu - N_R$ mixing

$$\Gamma(\theta \to \nu\nu) \propto (m_\nu/M_N)^4 \propto (m_\nu/f)^4$$

$$\Gamma(\theta \to e^+ e^-) \propto \alpha_W\, (m_\nu/M_N)^4 \propto \alpha_W\, (m_\nu/f)^4$$

⟹ decay suppressed by naturally large seesaw scale

Singlet-triplet DM extension:
M. Tortola's talk
Beriezinsky, Valle 93, Lattanzi, Valle 07',
Bazzocchi, Lattanzi, Riener-Sorensen, Valle 08',
Esteves, Joachim, Joshipura, Romao, Tortola, Valle 10'

A new pseudo-Goldstone DM framework

Frigerio, TH, Masso, 11'

⤷ in addition to provide the naturally large stabilizing scale the seesaw $\mathcal{L}$ can also provide:

- the source of explicit symmetry breaking $\Longrightarrow$ of m_{DM}
- the interactions producing the DM relic density
- with a justification for scalar DM at low scale with a mass radiatively "stable"

⤷ a possibility of a direct link between DM mass and DM relic density

A pseudo-Goldstone link between DM relic density and mass

Frigerio, TH, Masso, 11'

a Goldstone boson has no scalar potential

no mass

no scalar interaction

both induced by explicit sym. breaking

direct link between DM mass and relic density

if dominated by scalar interactions

suppose the explicit breaking term induces only a Higgs portal interaction:

$\mathcal{L} \ni \lambda\ \theta\theta\ H^\dagger H$

DM mass: $m_\theta^2 = \lambda\, v^2$ $\Longrightarrow$ DM at the electroweak scale or below

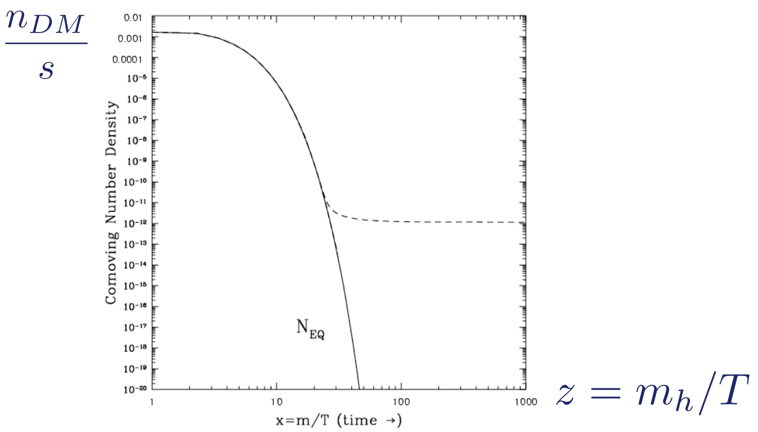
DM relic density from: $\theta\,\theta \leftrightarrow H H^\dagger$

DM relic density from the Higgs portal: $\mathcal{L} \ni \lambda \, \theta\theta \, H^\dagger H$

$$m_\theta^2 = \lambda v^2$$

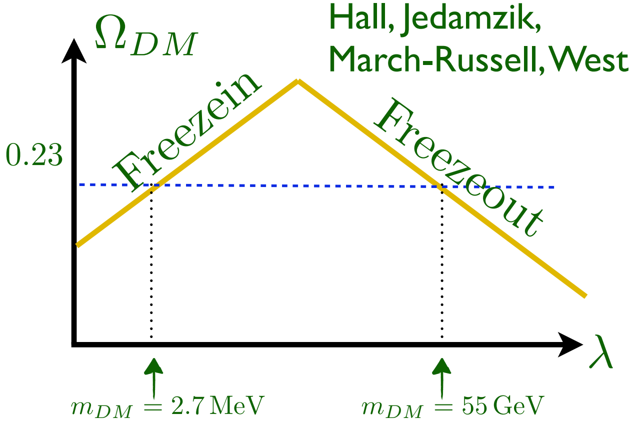
2 regimes

large λ coupling: freezeout
of DM annihilation
$\theta\theta \to hh, \, WW, \, ZZ, \, f\bar{f}$



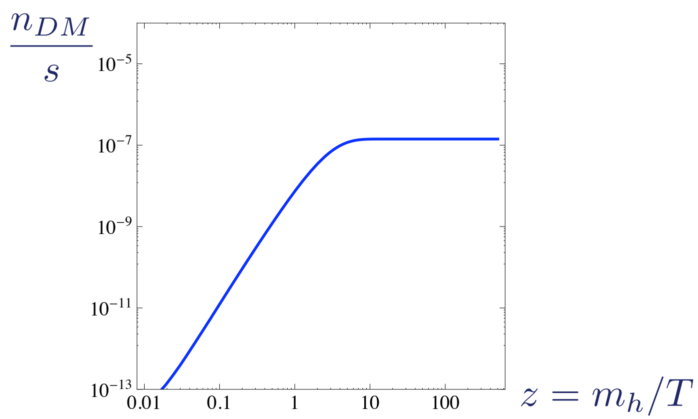
$$\Longrightarrow \; m_{DM} = 55\,\text{GeV} \quad (m_h = 120\,\text{GeV})$$

Farina, Pappadopoulo, Strumia 10'



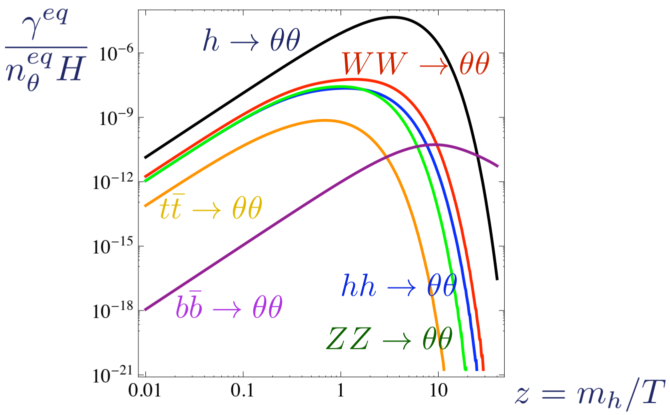
Hall, Jedamzik,
March-Russell, West 09'

small λ coupling: freezein
of DM pair creation
$hh, \, WW, \, ZZ, \, f\bar{f} \to \theta\theta$ and $h \to \theta\theta$



$$\Longrightarrow \; m_{DM} = 2.7\,\text{MeV}$$

Frigerio, TH, Masso, 11'



Collective breaking of a U(1) flavour symmetry

- collective breaking of global symmetry à la Hill and Ross '88
  - consider $U(1)_X$ flavour symmetry (instead of $U(1)_{B-L}$)
    - induces a θ mass only if several $M_{Nij} \neq 0$

allowed by $U(1)_X$

explicit $U(1)_X$ breaking

example: $N_{1,2}\ :\ Q^X_{N_1} = 0$

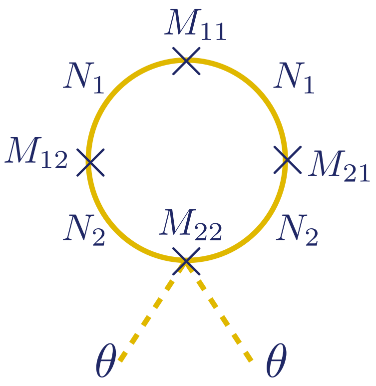
$$Q^X_{N_2} = 1 \implies M_N = \begin{pmatrix} M_{11} & M_{12} \\ M_{12} & M_{22}e^{i\theta/f} \end{pmatrix}$$

$$Q^X_\phi = 2$$

from $U(1)_X$ SSB

$$\implies m_\theta^2 \sim \frac{1}{8\pi^2}\,\frac{M_{11}M_{12}M_{22}M_{21}}{f^2}\,\ln\frac{\Lambda^2}{\mu^2}$$

← if any of $M_{ij} = 0$ we recover an exact $U(1)$



$\Downarrow$

logarithmic only

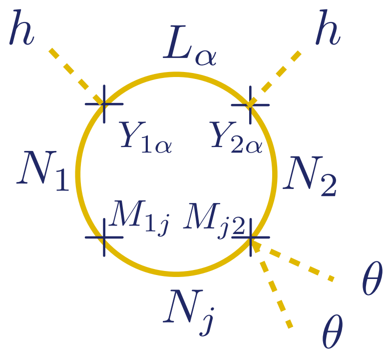
$\Downarrow$

mass not quadratically sensitive to the cutoff

Inducing the pseudo-Goldstone-Higgs portal

Frigerio, TH, Masso, 11

other possible realization of collective breaking involving both Majorana and Dirac terms:



$\Longrightarrow$ Higgs portal: $\lambda = \dfrac{1}{4\pi^2}\dfrac{M_{12}(M_{11}+M_{22})}{f^2} Y_{1\alpha}Y_{2\alpha} \log\dfrac{\Lambda^2}{\mu^2}$

$$m_\theta^2 = \lambda v^2 = \frac{1}{4\pi^2}\frac{M_{12}(M_{11}+M_{22})\, m_{1\alpha}^D\, m_{2\alpha}^D}{f^2} \log\frac{\Lambda^2}{\mu^2}$$

$\uparrow$

$$\mathcal{L} \ni \lambda\ \theta\theta\ H^\dagger H$$

example: $Q^X_{N_1} = -1,\ Q^X_{N_2} = 1,\ Q^X_\phi = 2,\ Q^X_\nu = 1$

NB: - to avoid generation of a DM tadpole, the easiest way is to assume CP symmetry

- if reheating temperature very high and ϕNN couplings large enough the relic density can be produced also from $NN \to \theta\theta$ pair production

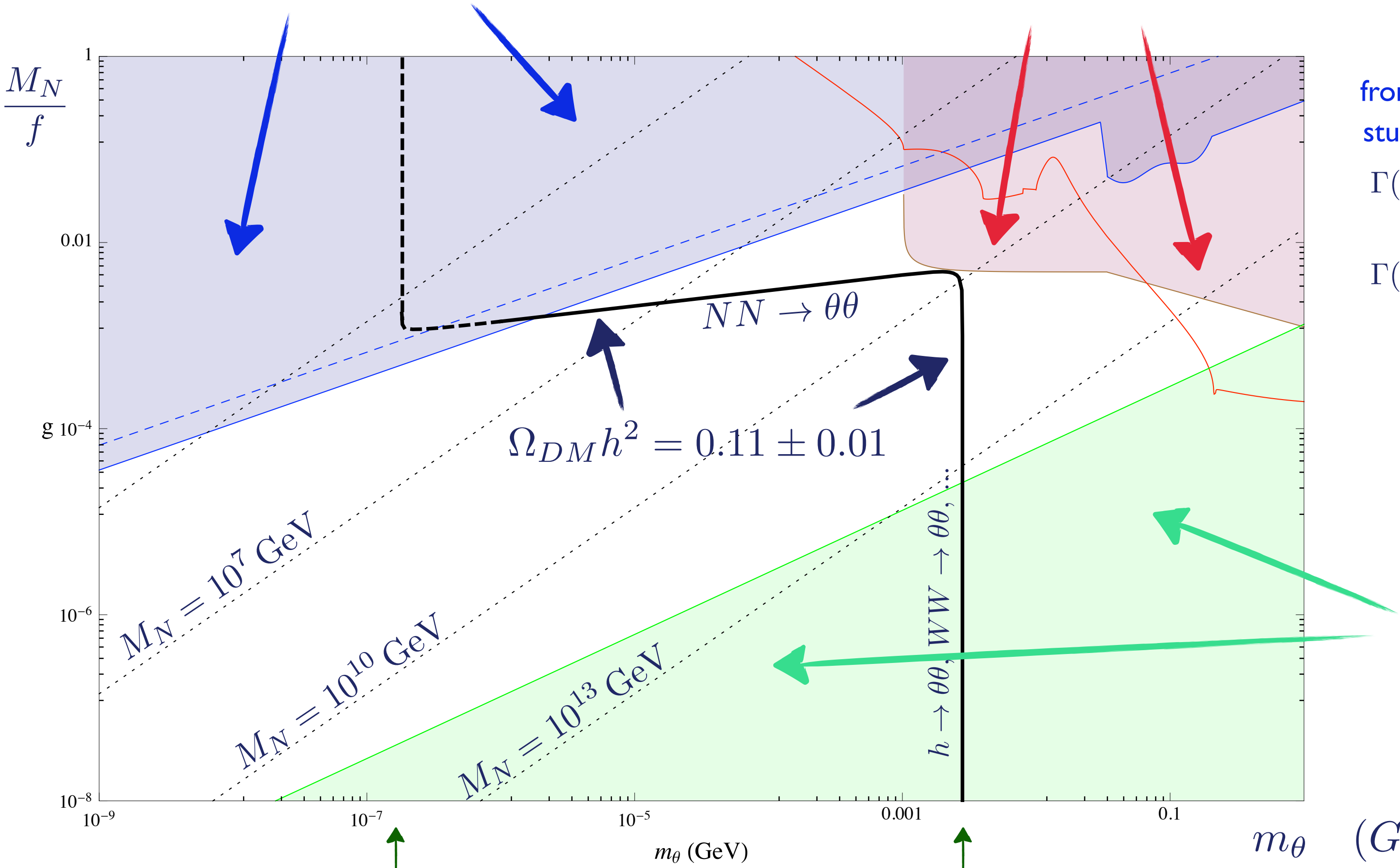
Compilation of constraints

Frigerio, TH, Masso, 11

$\Gamma(\theta \to \nu\nu) \propto m_\theta\, m_\nu^4/f^4$ too large

$\Gamma(\theta \to e^+e^-) \propto \alpha_W\, m_\theta m_e^2 m_\nu^2 M^2/f^2$ too large

$g \equiv \dfrac{M_N}{f}$



from experimental constraint study on:

$\Gamma(DM \to \nu\nu)$:

Palomares-Ruiz 08'

$\Gamma(DM \to e^+e^-)$:

Bell, Galen, Petraki 10'

$f > M_{Planck}$

$m_\nu = 0.05\,\mathrm{eV}$

$m_\theta \quad (GeV)$

$m_{DM} = 0.15\,\mathrm{KeV}$

$m_{DM} = 2.7\,\mathrm{MeV}$

unique value if $T_{reheating} < M_N$ or $g \equiv M_N/f$ small

Summary

- The origin of particle DM stability is a fundamental question!

  Each UV or low energy scenario requires a very specific pattern in term of type of particle needed, energy scale, ..., which leads to a specific phenomenology

  - long range dark force
  - intense flux of cosmic rays, γ-lines, ...
  - GUT specific realizations
  - specific DM mass
  - relic density/DM mass link
  - ....

- Pseudo-Goldstone setup: seesaw interactions assuming a U(1) flavour symmetry:

  - can provide the explicit breaking source $\Longrightarrow m_{DM}$
  - generate the DM relic density $\hookrightarrow m_{DM} \propto v_{EW}$
  - with a one-to-one link between m_{DM} and Ω_{DM} $\Longrightarrow m_{DM} = 2.7\,\mathrm{MeV}$
  - that can be probed by $DM \to \nu\nu$ and $DM \to e^+e^-$ searches

Backup

DM stability in non-susy SO(10) setups: scalar case

Kadastik, Kannike, Raidal 09'

add a16 scalar representation:

DM is a combination of a scalar doublet and a scalar singlet

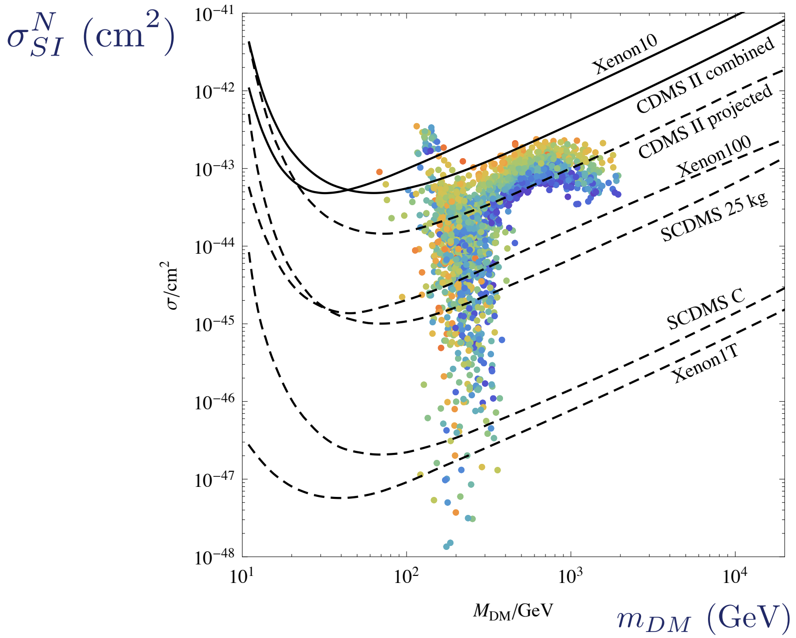
$\Downarrow$

inert doublet

similar phenomenology
with additional constraint:
$m_{DM} \gtrsim 100\,\mathrm{GeV}$

not for DAMA, CoGeNT

direct detection:



Huitu, Kannike, Raccioppi, Raidal 10'

+ long lived DM partners at LHC

DM stability in non-susy SO(10) setups: fermion case

Frigerio, TH 09'

add a 45 or 54 fermion representation:

DM is the neutral component of a fermion triplet $\Sigma^+, \Sigma^0, \Sigma^-$

$\Downarrow$

advantage that the DM triplet can drive gauge coupling unification

$\Downarrow$

as in split susy but without susy

low energy pheno is as for a generic fermion triplet:

- relic density requires $m_{DM} \simeq 2.7\,\mathrm{TeV}$ Cirelli, Fornengo, Strumia 06'
- $\sigma^N_{SI} \sim 10^{-45}\,\mathrm{cm}^2$
- indirect detection: - too many antiprotons for explaining e^+excess of Pamela
  - $DM\,DM \to \gamma\gamma$ expected to give γ-lines with a rate than can be probed at atmospheric Cerenkov telescopes

Hisano et al 04'; Cirelli, Franceschini, Strumia 08'

DM stability from unbroken U(1) gauge group

→ as for the e^-: stable because lightest charged particle under a U(1)

→ the simple adjunction of a new QED structure for a single fermion gives a viable DM candidate!!

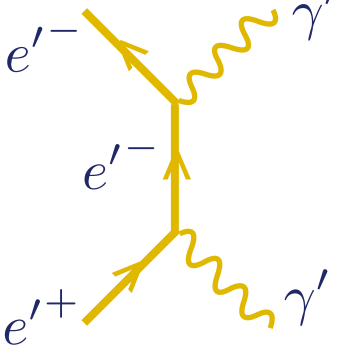
Ackerman, Buckley, Carroll, Kamionkowski 08'
Feng, Tu, Yu 08'; Feng, Kaplinghat, Tu, Yu 09'
Foot at al. 06'-10'

$$\mathcal{L} = \mathcal{L}_{SM} + \underline{\mathcal{L}_{QED'}}$$

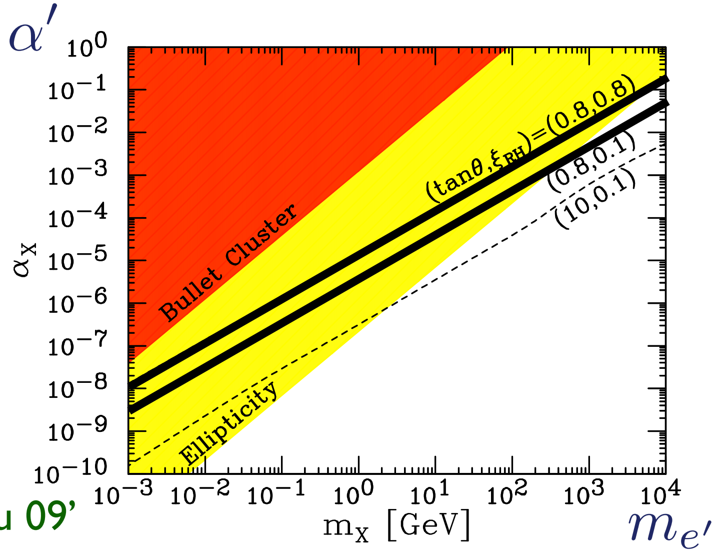
$$\hookrightarrow \mathcal{L}_{QED'} = \overline{\psi}_{e'}(i\not{\partial} - e\not{A}_{\gamma'} - m_{e'})\psi_{e'}$$

$$\downarrow \gamma' \qquad \downarrow e'^{\pm} \Rightarrow \text{stable}$$

⇒ $e'^{\pm}$ relic density



→ depends on $m_{e'}$, α', $\xi \equiv T_{\gamma'}/T_\gamma$



Feng, Kaplinghat, Tu, Yu 09'

DM stability from accidental symmetry: Minimal Dark Matter

Cirelli, Fornengo, Strumia 06'
Cirelli, Strumia, Tamburini 07'

- as the p^+ in the SM
- without adding any new gauge group, large $SU(2)_L$ multiplet cannot have any renormalizable interactions with SM fields due to $SU(2)_L$ gauge invariance

(or dimension-5)

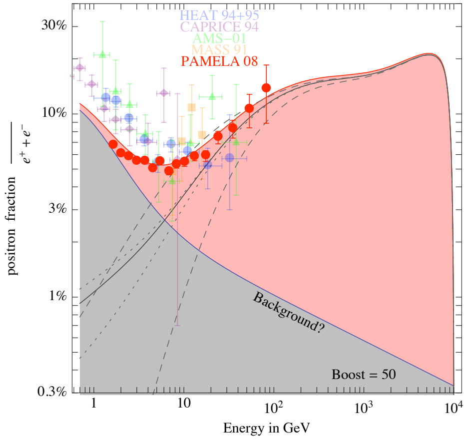
a fermion quintuplet, septuplet, ...

a scalar septuplet, nonuplet, ...

⇓

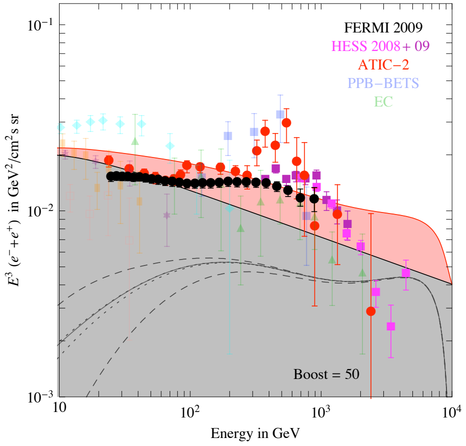
$$m_{DM} = (9.6 \pm 0.2)\,\mathrm{TeV}$$
$$\sigma_N^{SI} = 1.2 \cdot 10^{-44}\,\mathrm{cm}^2$$

nice fit of Pamela e^+ excess



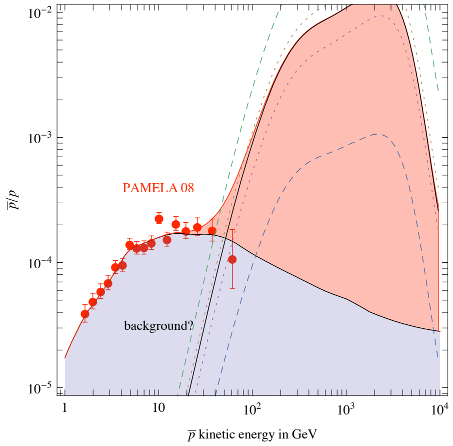
(large Sommerfeld resonance boost + need of ~ 50 astro boost)

$e^+ + e^-$ total flux



(m_{DM} too high for HESS cutoff)

$\bar{p}$ flux



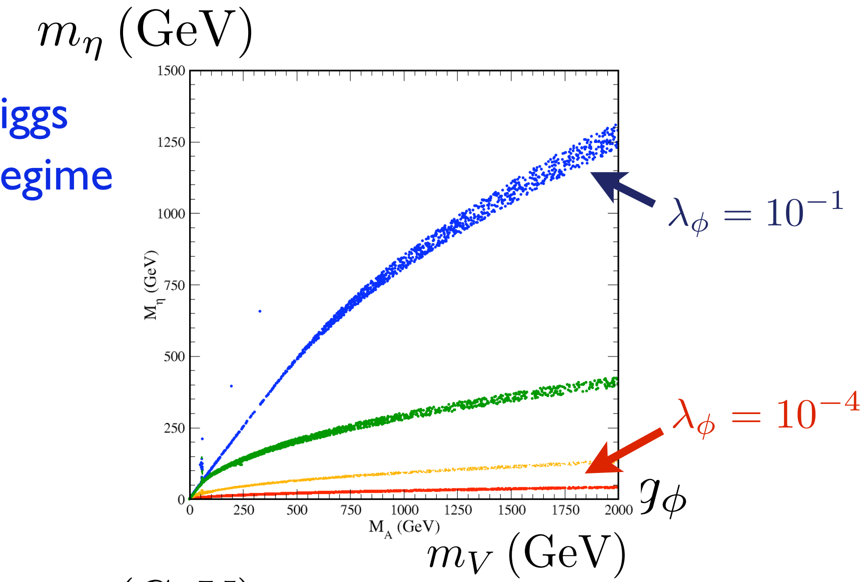
(m_{DM} high enough to avoid low energy excess)

prefers an isothermal profile for compatibility with galactic center and dwarf galaxy γ flux

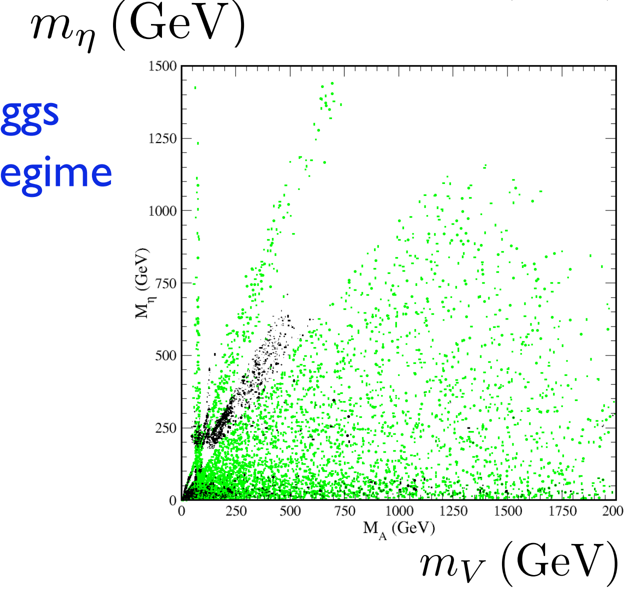
Hidden vector: relic density

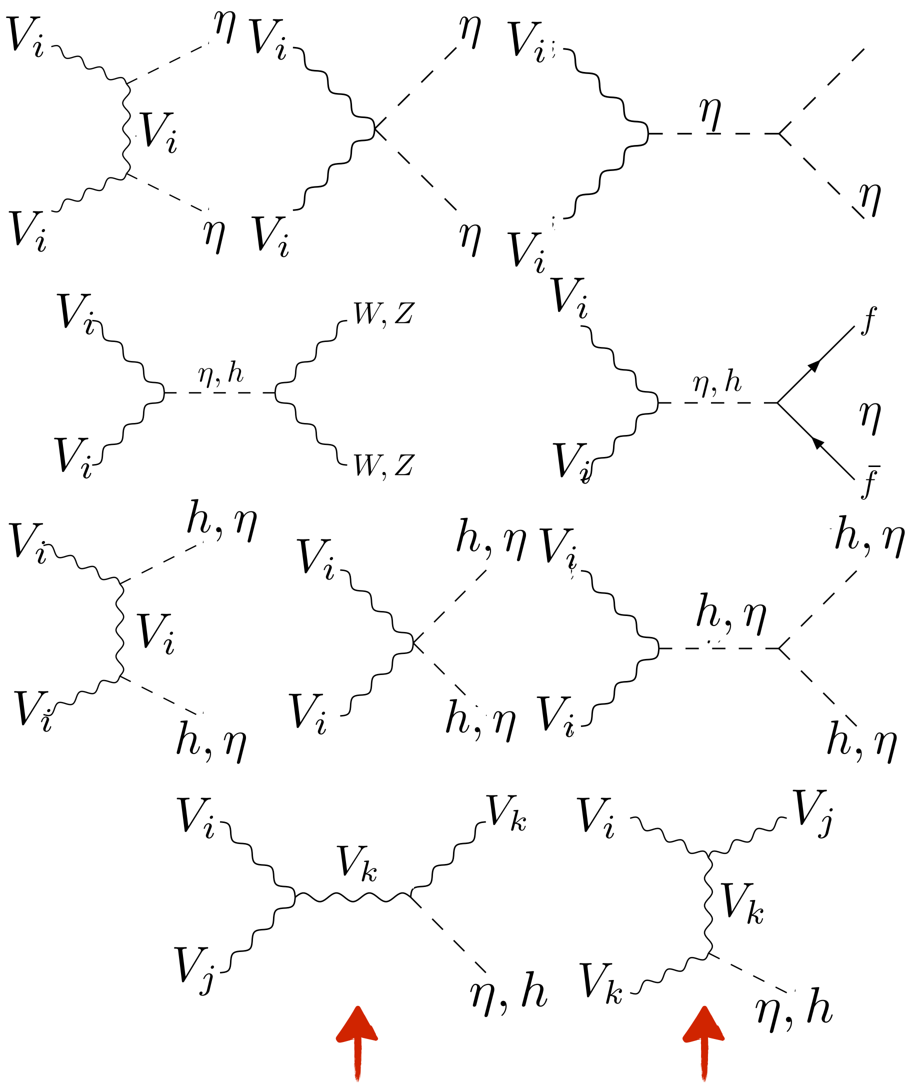
relic density from thermal freezeout

small Higgs portal regime



large Higgs portal regime

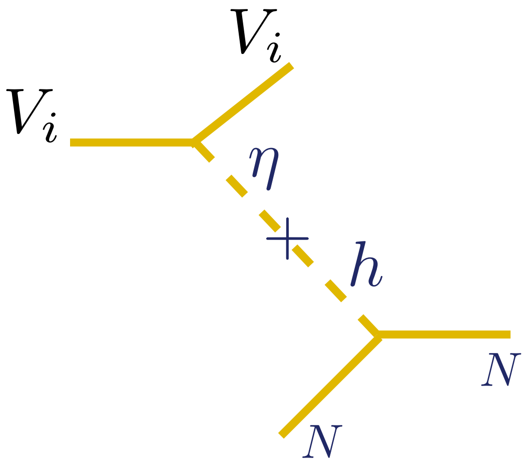


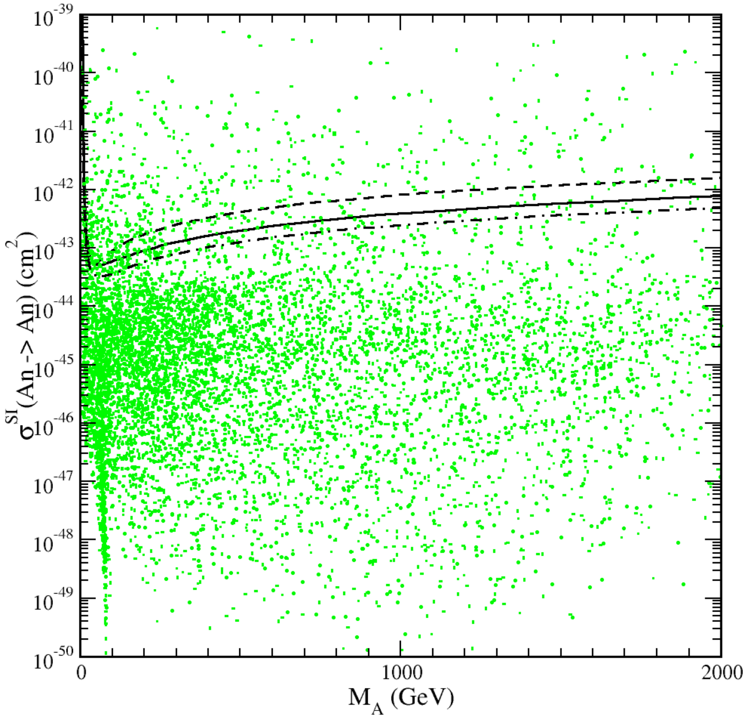


two DM to one DM particle annihilation

$$1\,\mathrm{MeV} < M_{DM} < 10\,\mathrm{TeV}$$

Hidden vector: direct detection





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 ⇒ rather suppressed

⇓

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

Bergstrom, Ullio, 97' 98';Bern, Gondolo, Perelstein 97';
Bergstrom, Bringmann, Eriksson, Gustafsson 04', 05';
Boudjema, Semenov, Temes 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'

Dimension-6 operators breaking the custodial symmetry

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

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

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

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

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

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

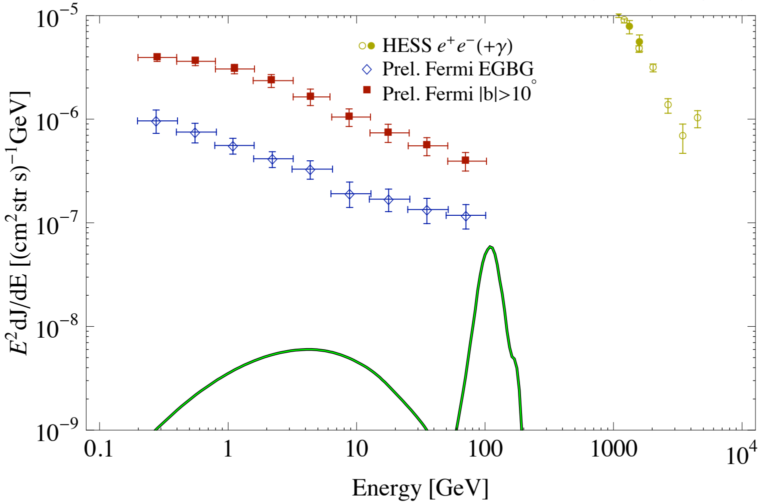
Benchmark	$Z\eta$	Zh	$\gamma\eta$	W^+W^-	$\nu\bar{\nu}$	e^+e^-	$u\bar{u}$	$d\bar{d}$
1	0.01	0.005	0.04	0.02	0.09	0.39	0.29	0.15
2	0.019	0.004	0.036	0.014	0.072	0.35	0.39	0.12
3	0.22	0.0002	0.73	0.0005	0.003	0.016	0.018	0.005

Flux of monochromatic γ-rays

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

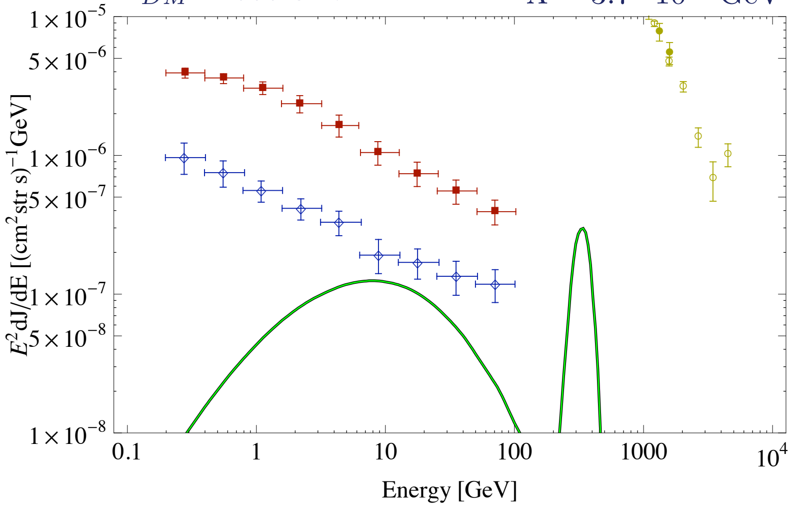
operator A & B

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



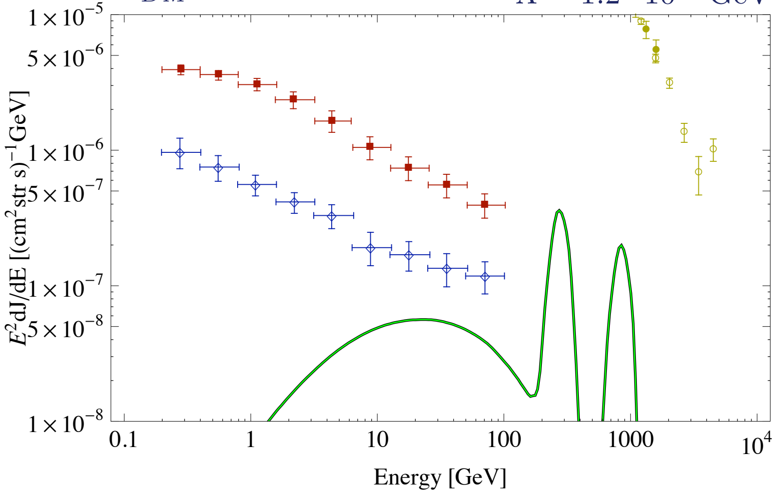
operator A & B

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



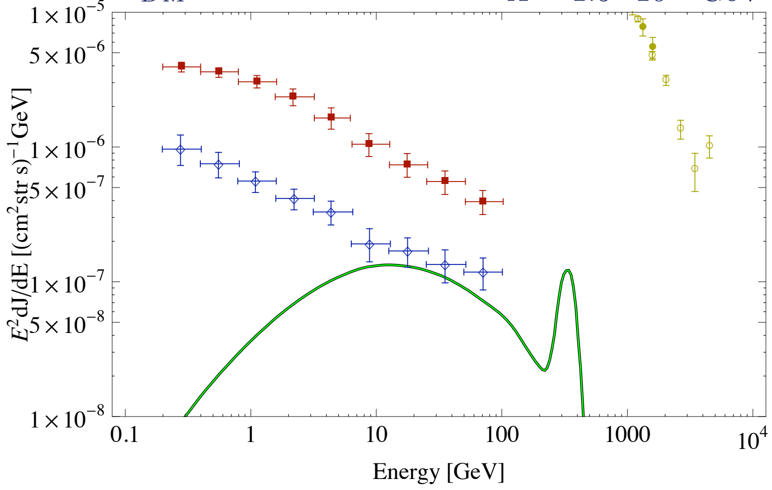
operator C

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



operator D

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



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

DM stability from accidental symmetry: Weakly interacting stable pions

Bai, Hill 10'

- QCD interactions conserve G-parity: $\underset{\overset{\uparrow}{+}}{\rho} \to \underset{\overset{\uparrow}{-}}{\pi}\underset{\overset{\uparrow}{-}}{\pi}$ but $\rho \cancel{\to \pi\pi\pi}$
- pions would be stable if there were only QCD
- but G-parity is not conserved by
  - weak interactions ($V - A$ structure)
  - hypercharge interactions

⇒ assume a new QCD structure with new quarks ψ with
- no hypercharge
- vector weak interact.

⇓

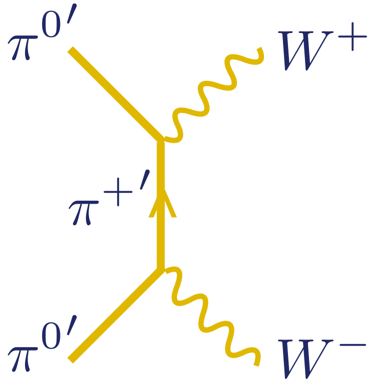
$$\psi_L = \text{doublet}$$
$$\psi_R = \text{doublet}$$

⇓

G-parity is exactly conserved

⇓

the $\pi^{0\prime}$ is stable and is a WIMP



$$m_{DM} = 100\,\text{GeV} \;- 2\,\text{TeV}$$
$$\sigma_N^{SI} \sim 10^{-45}\,\text{cm}^2$$

but dim-5 operators breaking G-parity are allowed ⇒ DM decay would be too fast

Other naturally stable DM candidates

- DM stability from small couplings (suppressed by heavy scale) and/or small DM mass:
  - axion P. Sikivie's talk
  - KeV right-handed neutrino F. Bezrukov's talk
  - gravitino
  - ...

Servant, Tait 06', ...

- KK parity in Universal Extra Dimension models (assuming orbifold,...)
- $U(1)_{B'}$ in technicolor models Gudnason, Kouvaris, Sannino 06'
- DM stability from a flavour symmetry Hirsch, Morisi, Peinado, Valle 10'
- .....

More Backup

Relic density

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

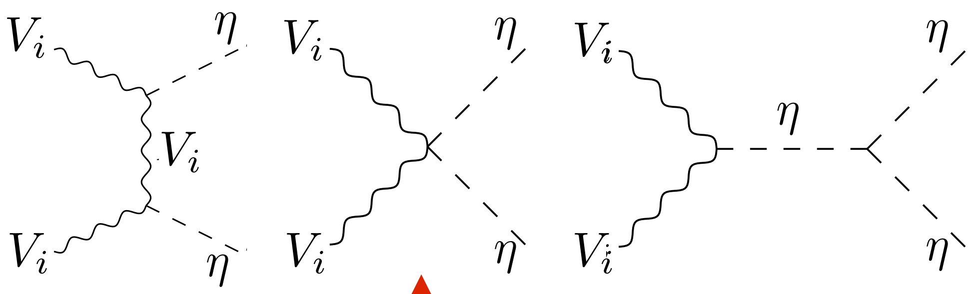
η with h :due to λ_m coupling

V_i with η :due to g_ϕ coupling

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

to two real η:

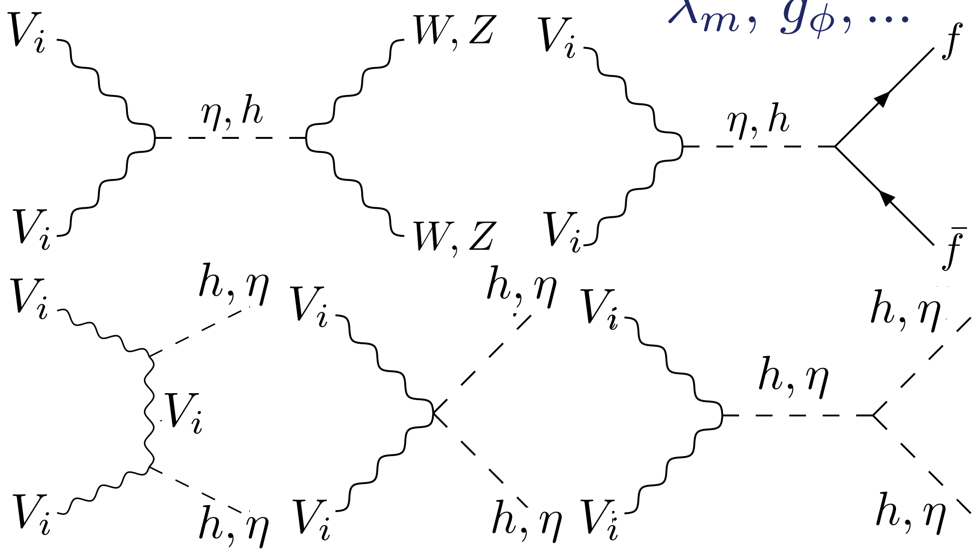
$g_\phi \; (+\lambda_\phi)$



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

with at least one SM part. in final state:

$\lambda_m, \; g_\phi, \ldots$



Relic density: additional new type of contribution

non abelian trilinear gauge couplings:

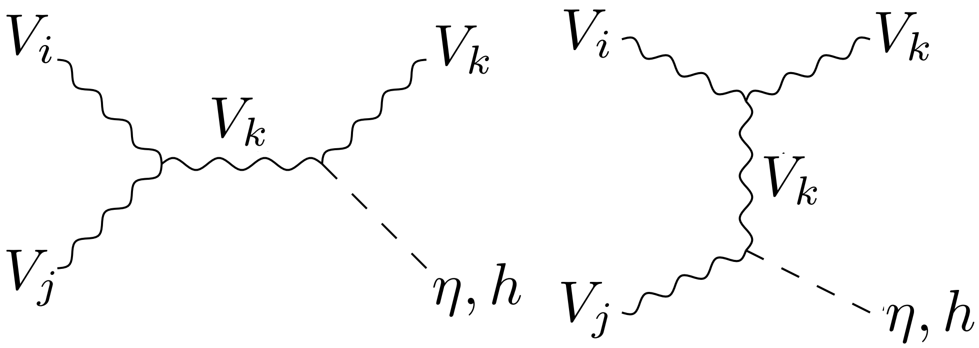
$$F^a_{\mu\nu}F^{\mu\nu a} \ni \varepsilon_{ijk}\partial_\mu A_{i\nu}(A^\mu_j A^\nu_k - A^\nu_j A^\mu_k)$$

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

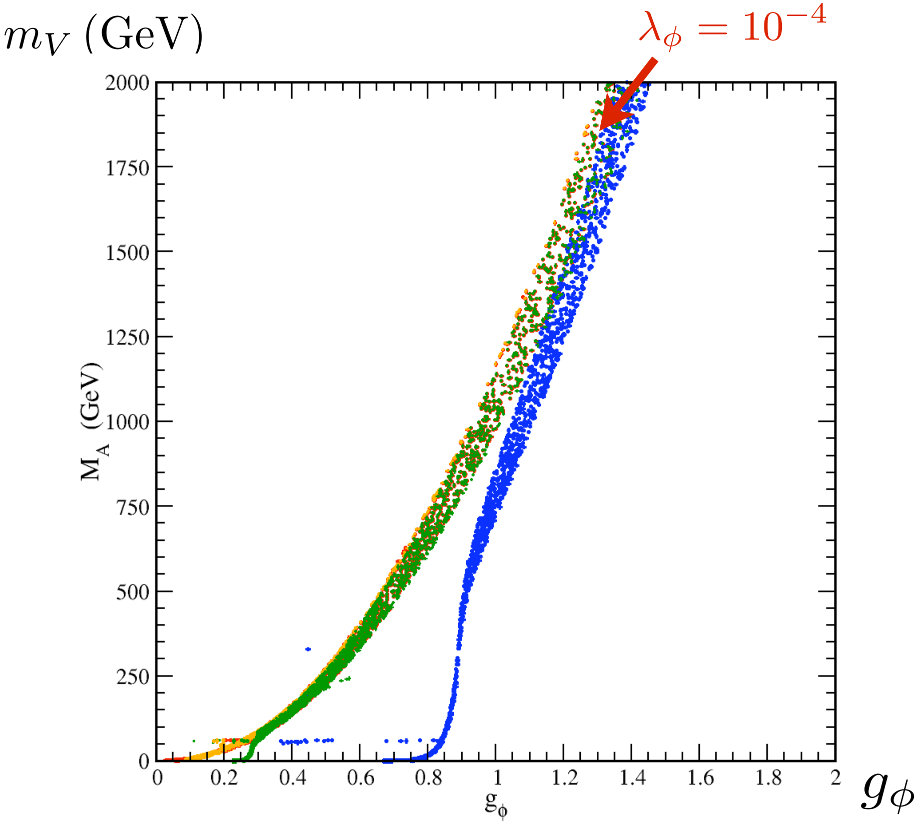
⇒ if λ_ϕ also small:

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

$$\Downarrow$$

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

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



Small Higgs portal regime

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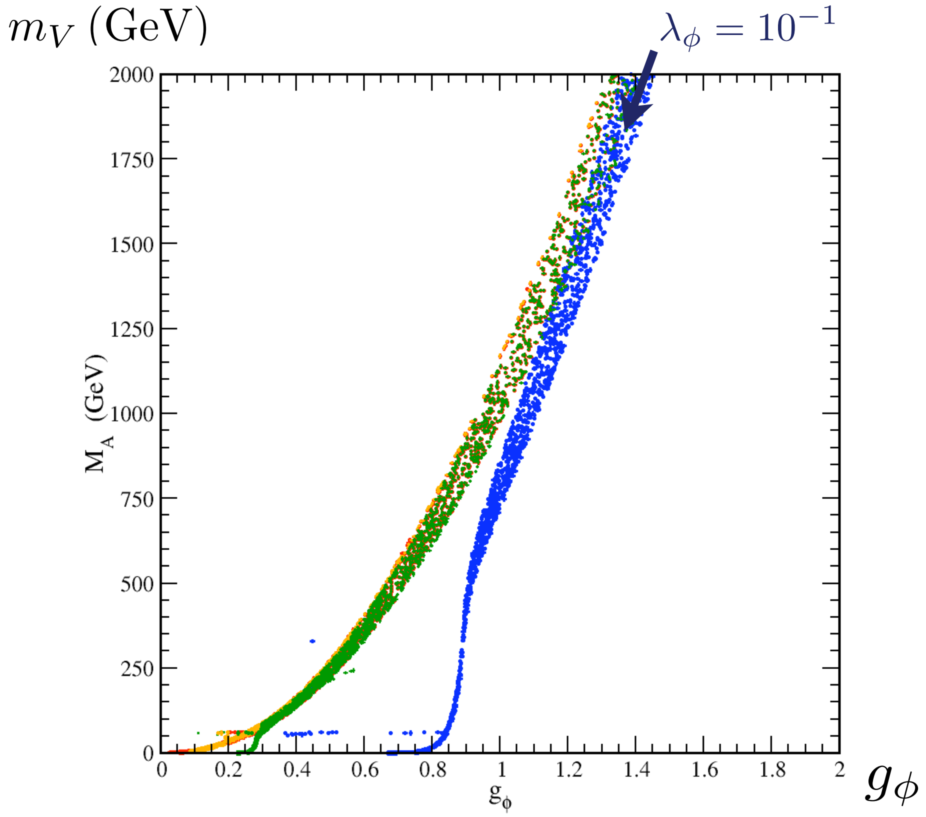
depend only on $g_\phi \,, v_\phi, \lambda_\phi$ with $m_V = \dfrac{g_\phi v_\phi}{2}$, $m_\eta \simeq \sqrt{2\lambda_\phi}\, v_\phi$

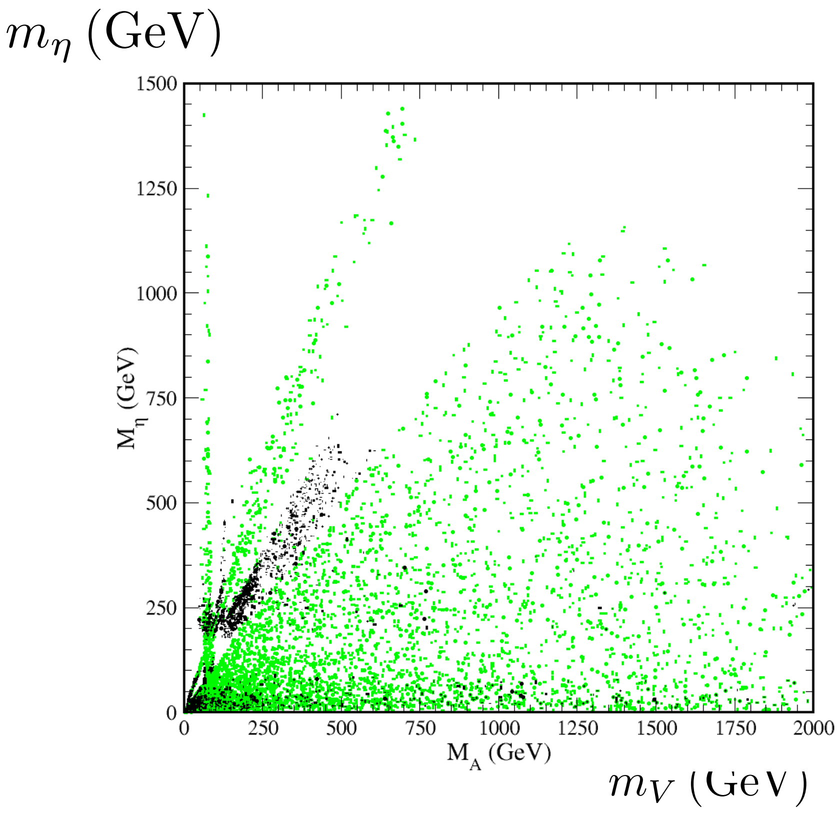
$\Rightarrow$ if λ_ϕ large:



Large Higgs portal regime

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

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



⇓

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

⇓

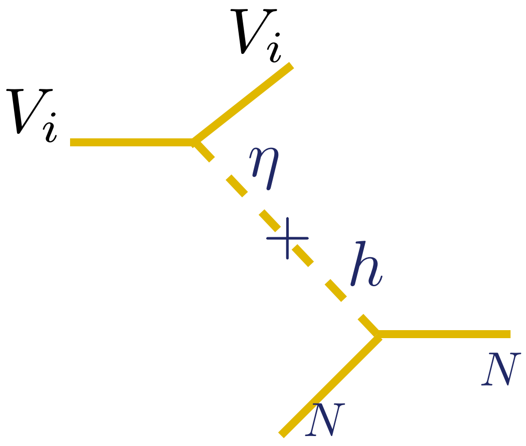
T parameter constraint:

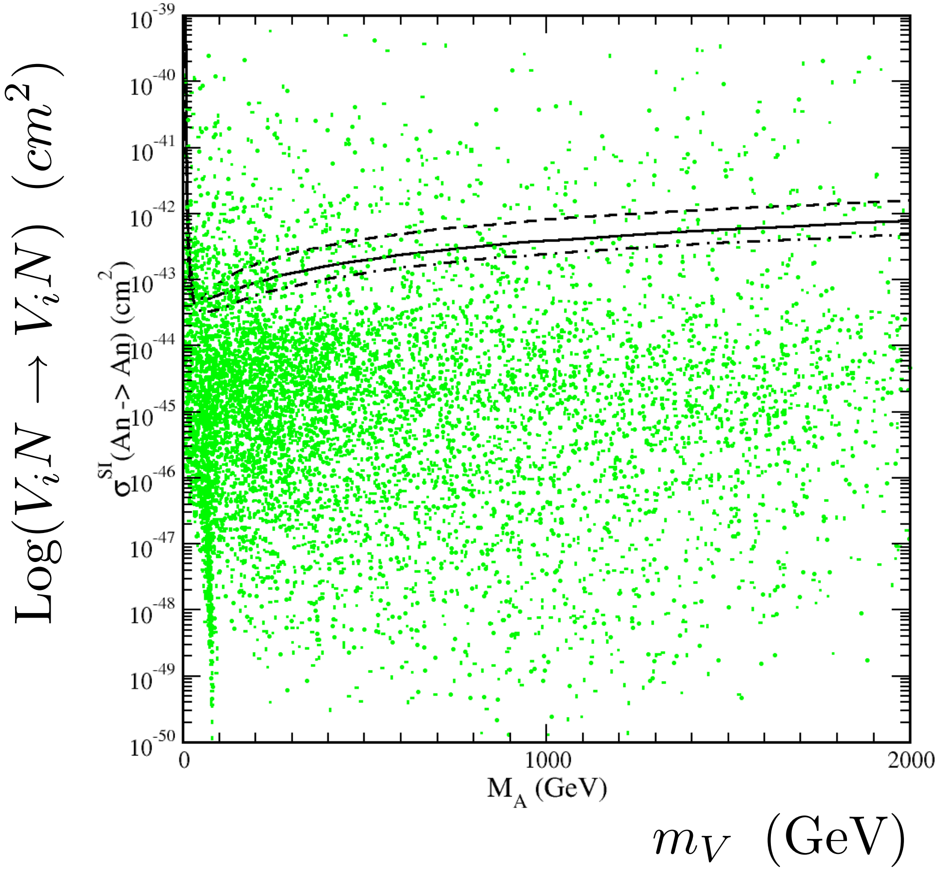
if $m_h = 120\,\mathrm{GeV}$ ⇒ $m_\eta <\sim 240\ \mathrm{GeV}\ (3\sigma)$

↪ or larger if non maximal mixing

if $m_\eta = m_h$ ⇒ $m_h = m_\eta < 154\ \mathrm{GeV}\ (3\sigma)$

Hidden vector: direct detection





⇒ can saturate the experimental bound easily

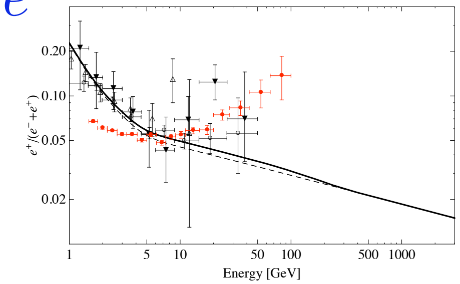
Hidden vector: cosmic ray fluxes

operator A & B

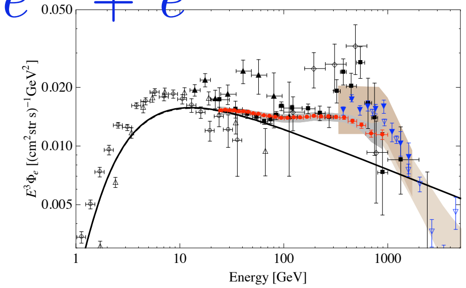
$m_{DM} = 300\,\text{GeV}$

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

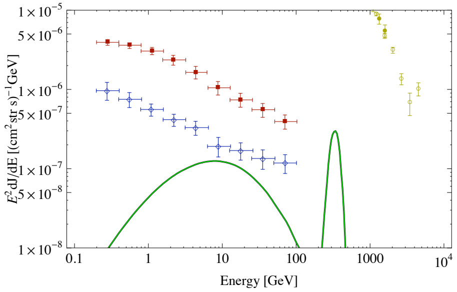
e^+



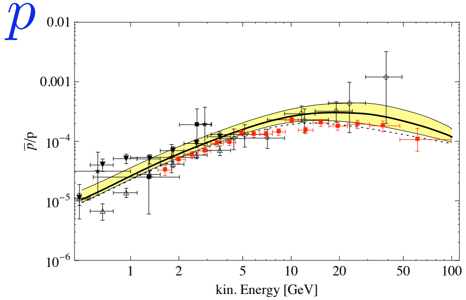
$e^+ + e^-$



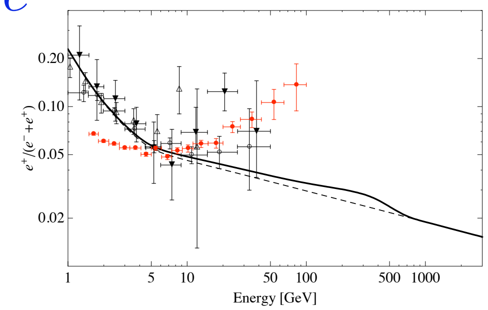
γ



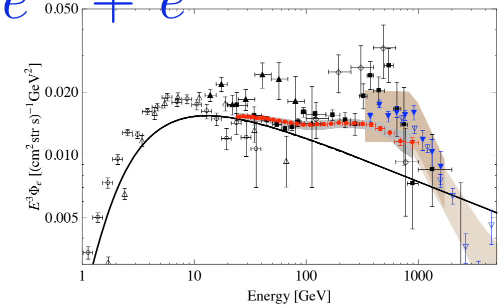
$\bar{p}$



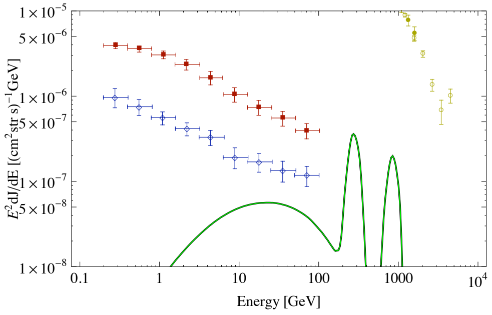
e^+



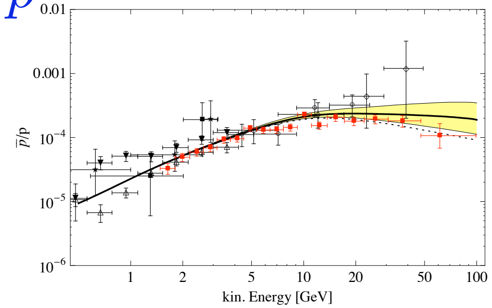
$e^+ + e^-$



γ



$\bar{p}$



operator C

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

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

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: $V_\mu^0 \equiv \dfrac{\phi^\dagger D_\mu \phi - \tilde{\phi}^\dagger D_\mu \tilde{\phi}}{\sqrt{2}}$

} SO(3) triplet

$\Downarrow$

stable DM candidates!

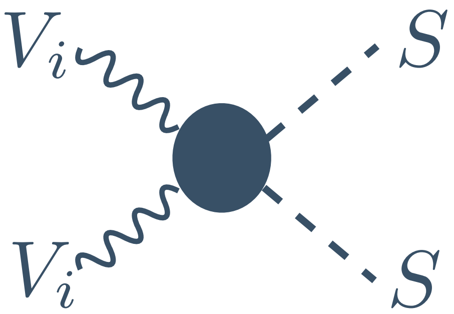
Relic density in the confined regime

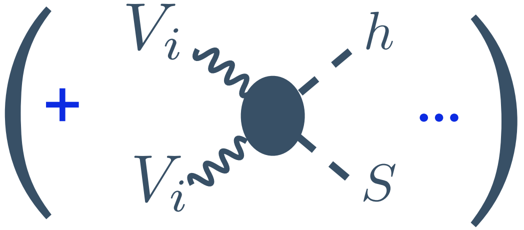
→ strongly interactive massive particle (SIMP)

→ annihilation cross section cannot be calculated perturbatively

⇓

expected dominant channel:





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

⇓

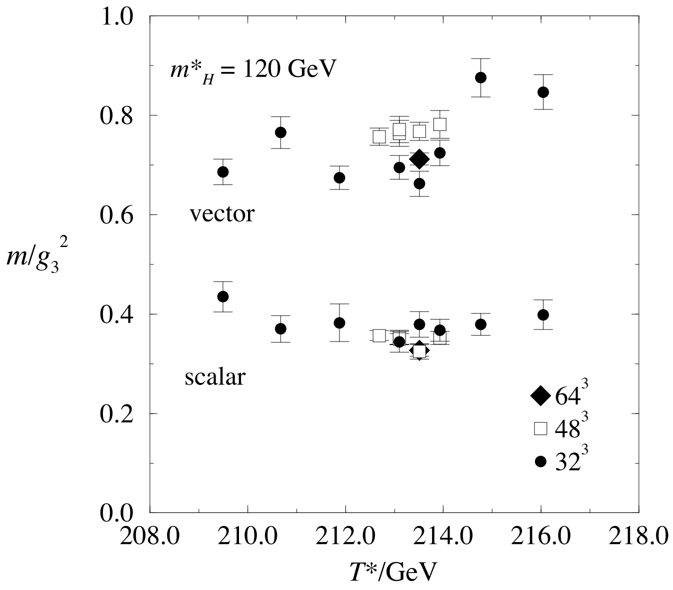
$A = 10-50$

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

⇒ 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:

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

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

$$\Downarrow$$

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

$$\Downarrow$$

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

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