Hidden vector Dark Matter

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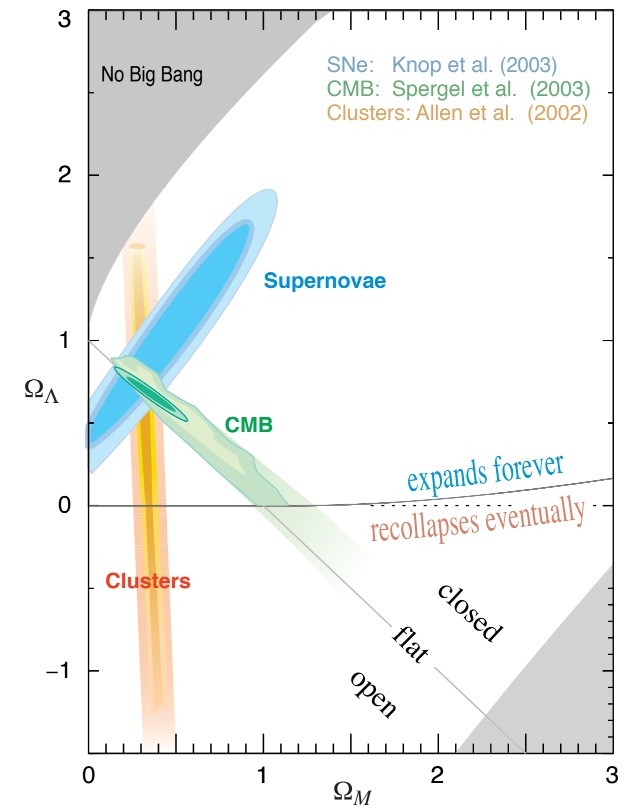
Dark Matter: Evidences

Existence of a neutral stable massive particle:

-At galactic scale: velocity distribution of stars

-At galaxy cluster scale: -velocity distribution of galaxies
-bullet cluster

-At cosmological scales: CMB data (WMAP), supernovae,....



lead consistently to:

$$\Omega_{DM} = 0.20 \pm 0.03$$

Dark Matter: 3 main questions

-Nature of DM?

-At which scale?

-Why is it stable?

Dark Matter: WIMP mechanism

Relic density from annihilation freeze out:

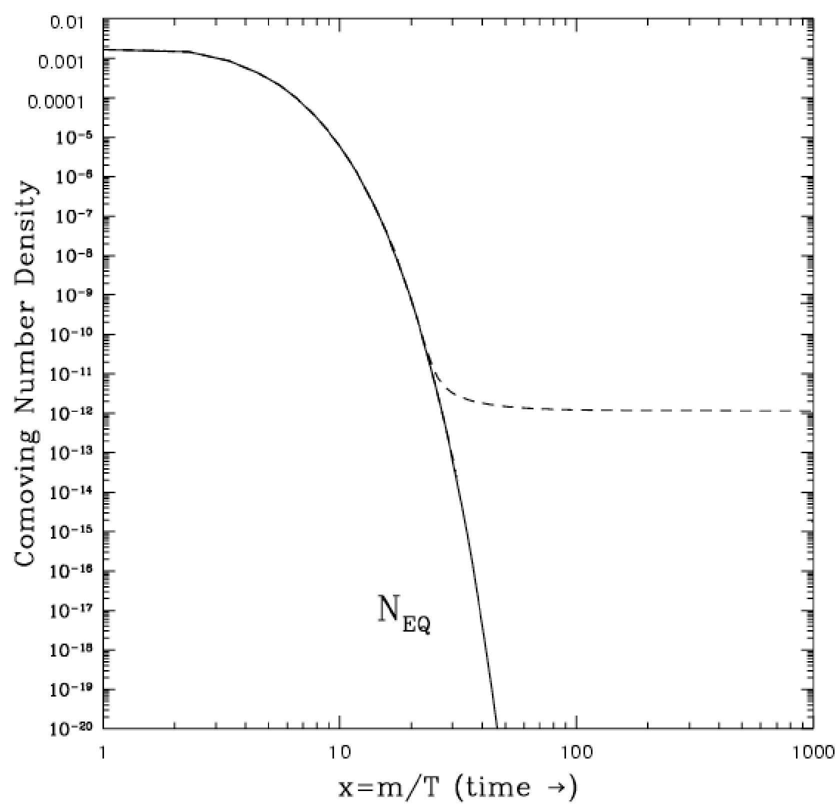
- Down to $T \sim m_{DM}$, DM is in thermal equilibrium: $n_{DM} \simeq n_{DM}^{Eq}$
- For $T < m_{DM}$: $n_{DM} \propto e^{-m_{DM}/T}$ ← Boltzmann suppression

freeze out of the annihilation at $T = T_f$

$$\Omega_{DM}(T < T_f) \simeq \Omega_{DM}(T = T_f) \propto \frac{1}{\sigma_{annih.}(T = T_f)}$$

$$\sigma_{annih.} v_r \simeq 10^{-26}\,\mathrm{cm}^3/sec$$

⇒ If $\sigma_{annih.} \simeq g^4/m_{DM}^2$ and $g \sim 0.1 - 1$ one needs $m_{DM} \sim 1\ \mathrm{GeV} - 10\ \mathrm{TeV}$



Dark Matter: 3 main questions

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Dark Matter: 3 main questions

- Nature of DM?

- Why around electroweak scale?

- Why is it stable?

Dark Matter: 3 main questions

MSSM:

-Nature of DM? ← well motivated: superpartner

-Why around electroweak scale? ← well motivated: hierarchy problem...

-Why is it stable? ← not that well motivated: R-parity put by hand (even if motivated by proton decay)

Dark Matter: 3 main questions

Scalar singlet DM, inert doublet DM, fermion singlet DM,....:

-Nature of DM? ← motivated by minimality

-Why around electroweak scale? ← put by hand at right scale

-Why is it stable? ← not motivated: Z_2-parity put by hand

Dark Matter: 3 main questions

-Nature of DM? ← Scalar singlet DM, inert doublet DM, fermion singlet DM,....: motivated by minimality

-Why around electroweak scale? ← put by hand at right scale

-Why is it stable? ← not motivated: Z_2-parity put by hand

in contrast with all known stable particles which are stable due to a fundamental reason:

- γ: because massless (due to gauge symmetry)
- lightest ν: because lightest fermion (Lorentz sym.)
- e^-: because lightest charged particle under exact $U(1)_{em}$
- p^+: accidental sym. due to gauge SM sym. and particle content

Justifying DM stability from gauge sym. and particle content

→ starting point of this talk

Known examples:

- R-parity as remnant of gauge $U(1)_{B-L}$
- $SU(2)_L$ fermion quintuplet or scalar sevenplet: no possible interaction with SM fields causing its decay with dim < 6

  ⇒ lifetime larger than universe age if Lambda ~ M_{GUT}

  Cirelli, Fornengo, Strumia '06

- fermion SM singlet charged under a U(1) (with additional scalar to break it)

  Pospelov, Ritz, Voloshin '06

→ in all cases the stability is insured by a remnant Z_2

→ could we have other kinds of global symmetries???

Custodial symmetry $\Rightarrow$ DM stability

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

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

$\Downarrow$

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

ϕ gets a vev v_{ϕ}

$\Rightarrow$ 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 η = singlet

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

but obviously this cannot work in the SM $\leftarrow$ ($SU(2)_C$ associated to $SU(2)_L$ is broken by Yukawa's and θ_W)

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}

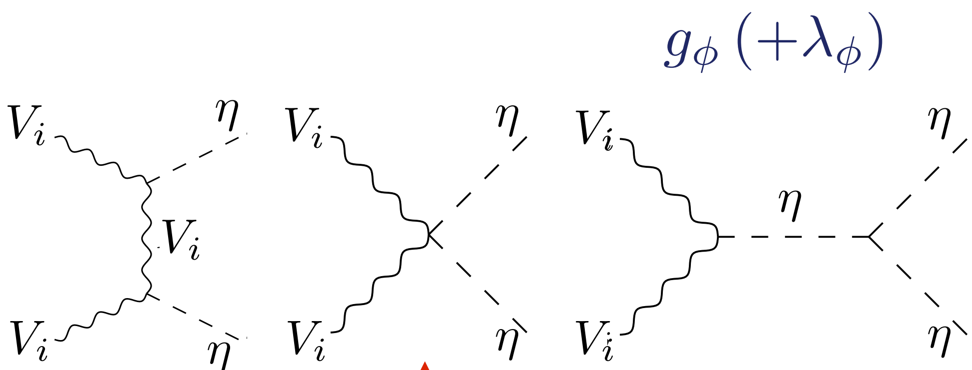
Relic density

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

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

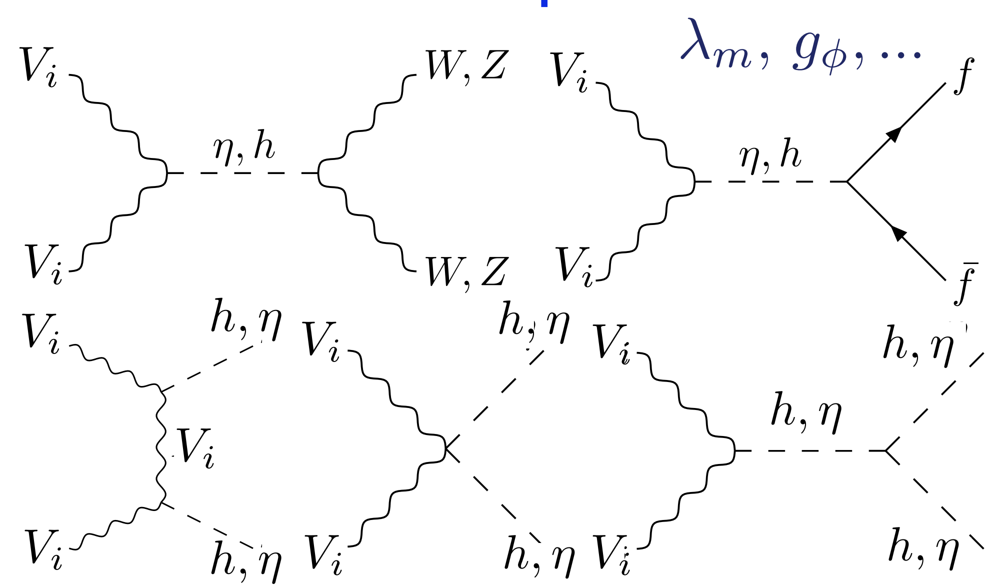
- $T < m_V$: $n_V^{eq.} \sim e^{-m_V/T}$ $\Rightarrow$ annihilation freeze out (WIMP)

to two real η:



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

with at least one SM part. in final state:



Relic density: additional new type of contribution

non abelian trilinear gauge couplings:

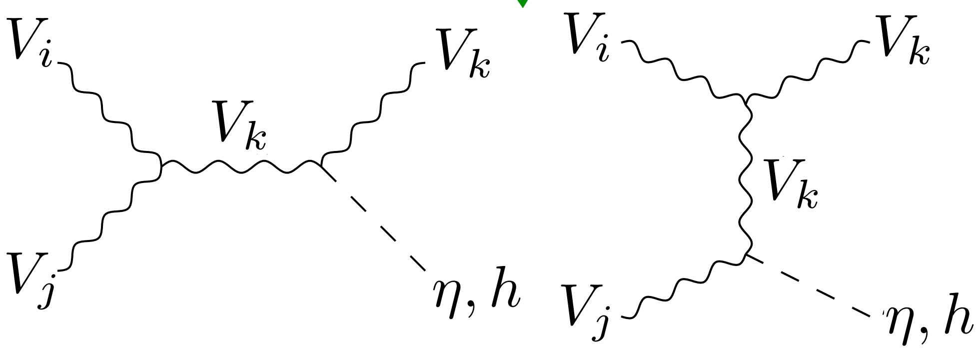
$$F^a_{\mu\nu} F^{\mu\nu a} \ni \varepsilon_{ijk} \partial_\mu A_{i\nu} (A^\mu_j A^\nu_k - A^\nu_j A^\mu_k)$$

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

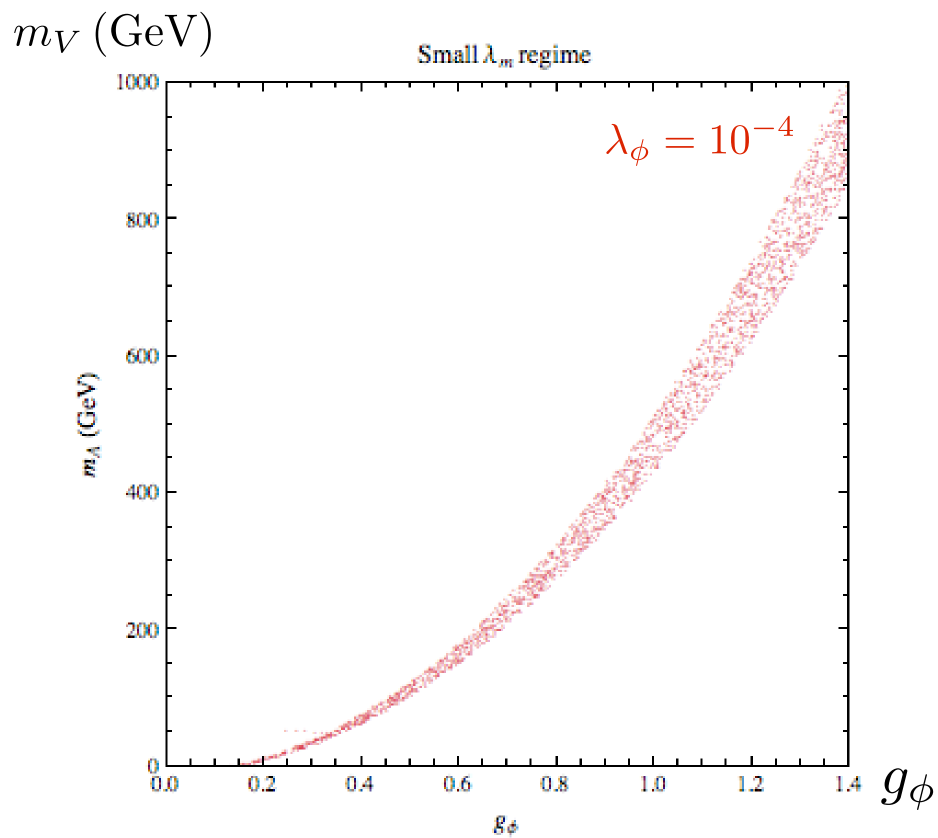
$\Rightarrow$ if λ_ϕ also small:

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

$\Downarrow$

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

$$\Rightarrow 1\,\text{MeV} \lesssim m_{DM} \lesssim 50\,\text{TeV}$$



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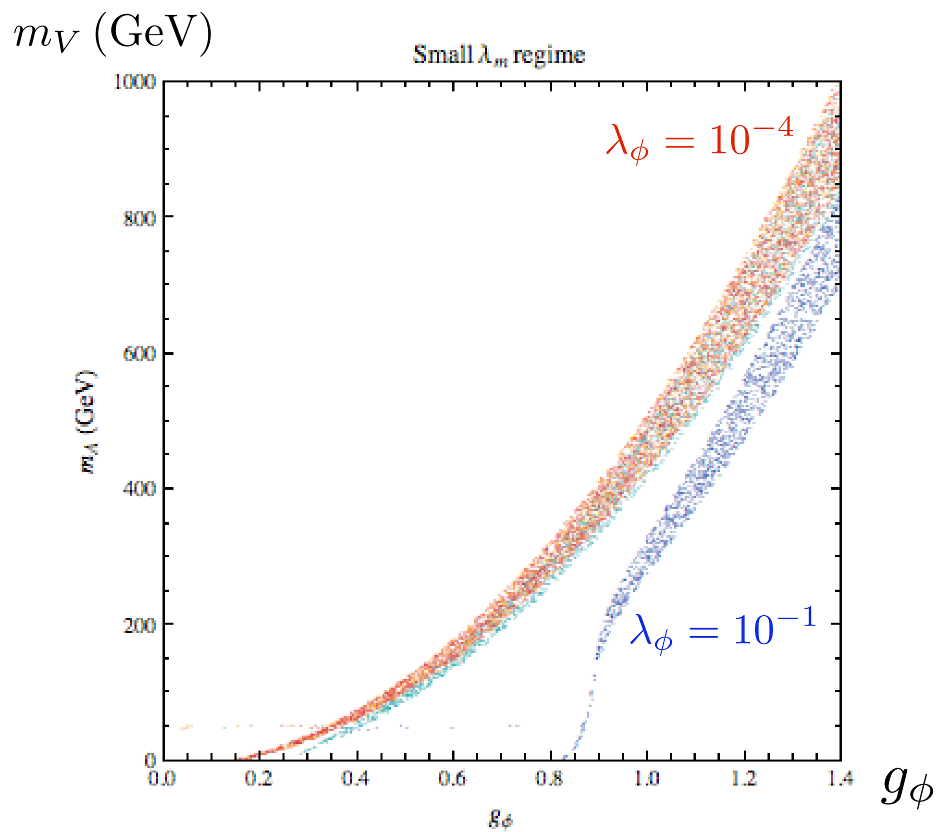
$\Rightarrow$ if λ_ϕ large:



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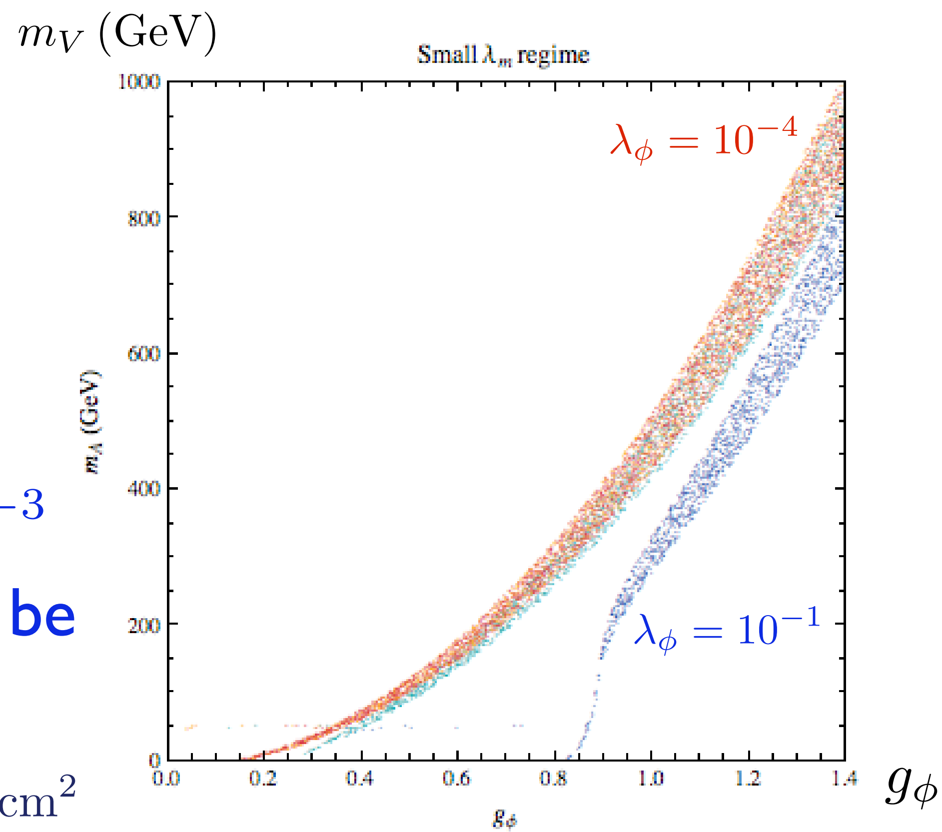


⇒ works very fine but difficult to test (if λ_m tiny)

but for example for $\lambda_m = 10^{-3}$ the direct detection rate can be of order the experim. bound

$\sigma(VN \to VN) \sim 10^{-44}\,\mathrm{cm}^2$

Large Higgs portal regime

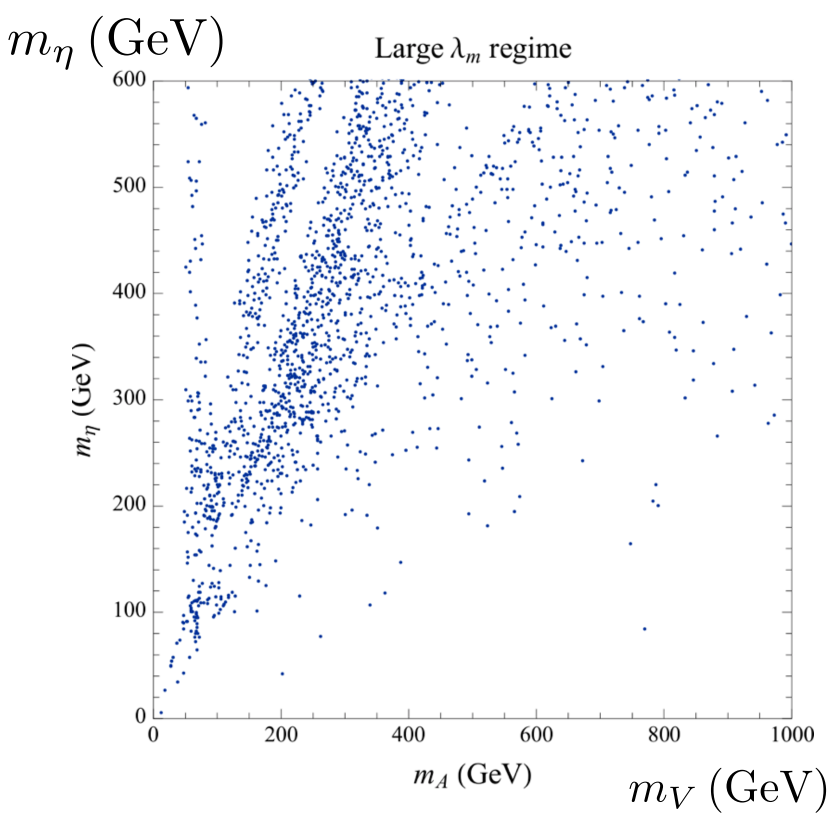
$\lambda_m \gtrsim 10^{-3}$ $\Rightarrow$ large $\eta - h$ mixing $\Rightarrow$ large hidden sector - SM mixing

→ 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

$\Downarrow$



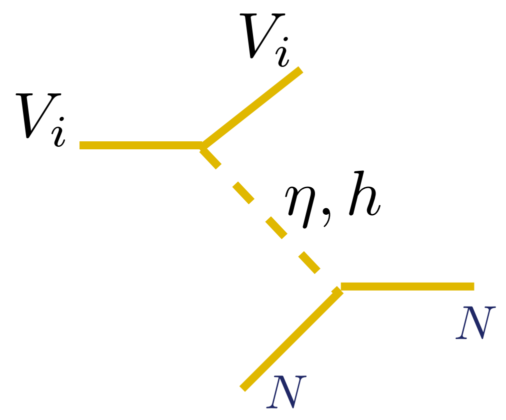
T parameter constraint:

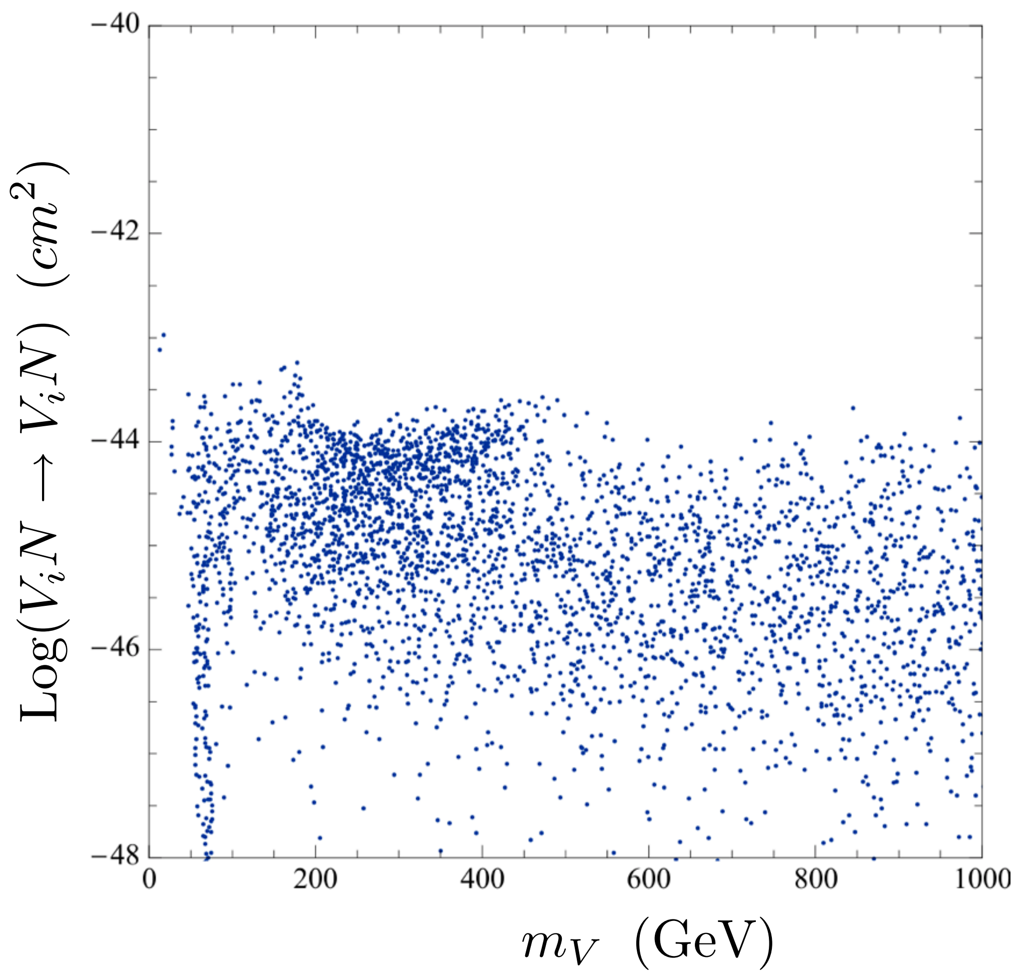
if $m_\eta = m_h \Rightarrow m_h = m_\eta < 154$ GeV (3σ)

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

→ or larger if non maximal mixing

Large Higgs portal regime: direct detection





⇒ can saturate the experimental bound for $m_V \lesssim 300\,\mathrm{GeV}$

⇒ large Higgs portal regime: very rich phenomenology

Pamela??? (the song of the siren)

observed excess of 10-100 GeV cosmic positrons

requires an annihilation to positron: $\sigma\, v_r \simeq 3 \cdot 10^{-23}\, \mathrm{cm}^3/sec$

V

Λ

$\sigma_{annih.}\, v_r \simeq 10^{-26}\, \mathrm{cm}^3/sec$

to get the right Ω_{DM}

$\Rightarrow$ need for a $10^3 - 10^4$ boost of positron production: unlikely ($\Rightarrow$ pulsars??)

but if one tries: - astrophysics: a factor 10 boost at most

- particle physics: Sommerfeld enhancement

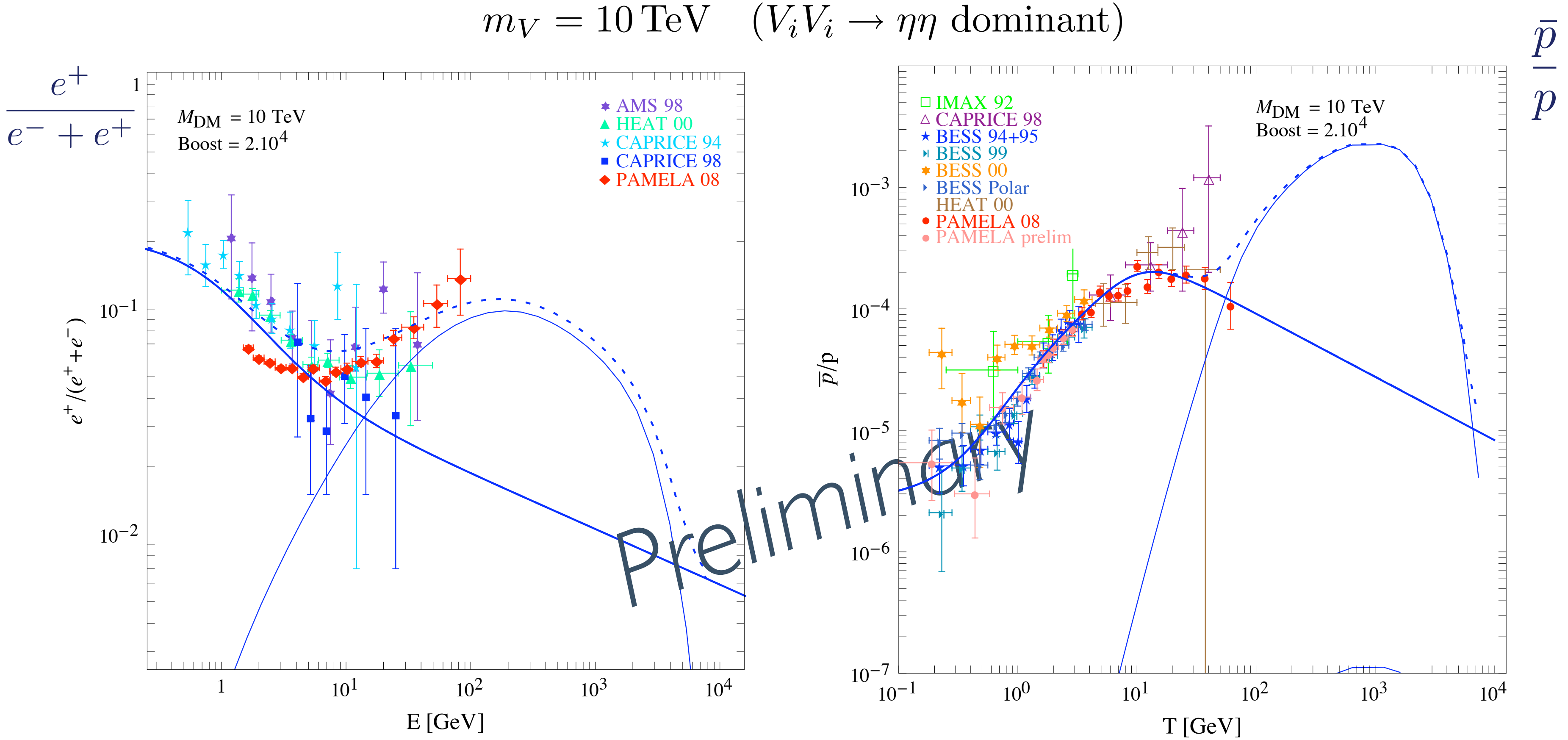
$\Downarrow$

from attractive long range force

First step: if boost large enough can we reproduce the Pamela spectrum?

yes easily: one example:

$$m_V = 10\,\mathrm{TeV} \quad (V_i V_i \to \eta\eta \text{ dominant})$$



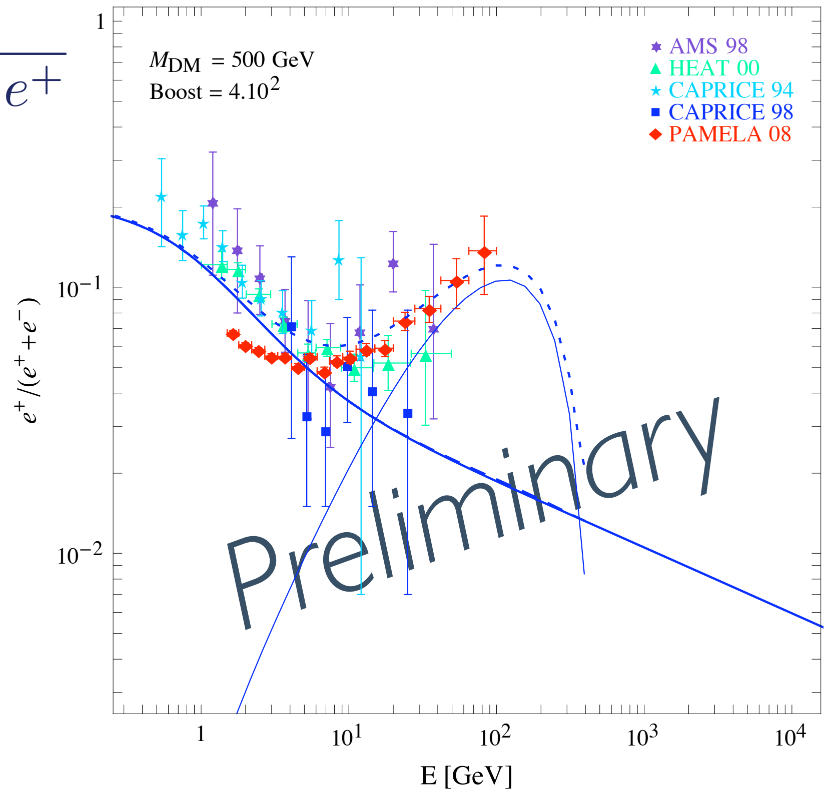
thanks to Gilles Vertongen

First step: if boost large enough can we reproduce the Pamela spectrum?

yes easily: 2nd example:

$$m_V = 500\ \mathrm{GeV} \quad m_\eta = 100\,\mathrm{MeV}$$
$$(V_i V_i \to \eta\eta\ \mathrm{dominant})\ \ \eta \to e^+ e^-$$

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



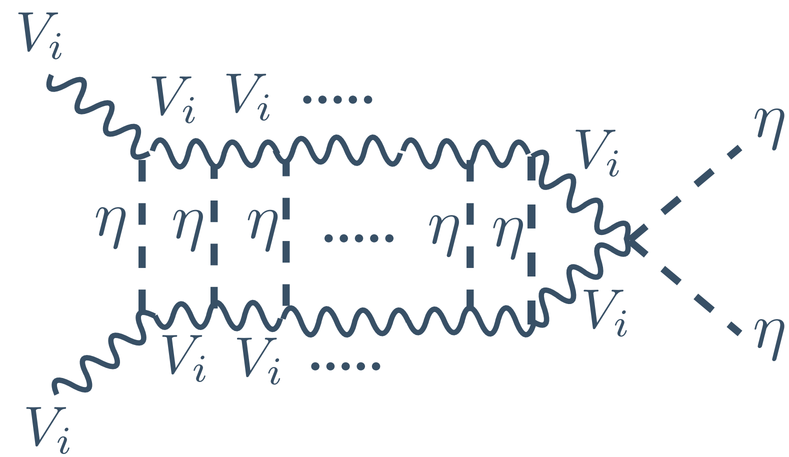
thanks to Gilles Vertongen

Second step: can we get a large enough Sommerfeld boost?

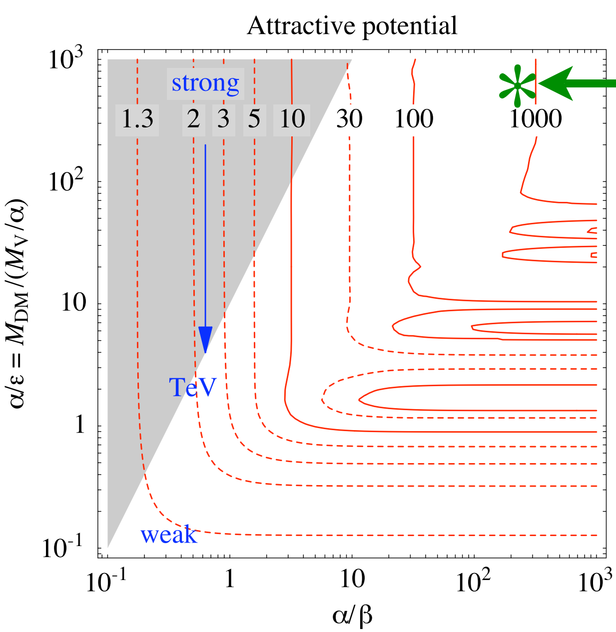
η mediated between 2 V_i is attractive:

⇓

Sommerfeld boost



Cirelli, Strumia, Tamburini '07



where we are for example with: $m_V = 500$ GeV, $m_\eta = 100$ MeV

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

⇒ apparently the boost is large enough

⇓

explicit realization of Arkani-Hamed, Weiner et al mechanism

What about the non-perturbative regime of this model?

T.H., M.Tytgat, arXiv:0902?

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

⇒ 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 ⇓ 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)

⇓

$A = 10 - 50$

$$\sigma_{annih.} \sim \frac{A}{\Lambda^2_{SU(2)}} \Rightarrow m_{DM} \simeq 20 - 200\,\mathrm{TeV}$$

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

Higher dimensional operator effects

no possible dim-5 (gauge invar.) operators destabilizing the vector DM particles: only dim-6 operators

$$\Downarrow$$

$$\frac{D^\mu \phi^\dagger F_{\mu\nu} D^\nu \phi}{\Lambda^2}\,,\ \cdots$$

$\Rightarrow$ for $m_V \simeq 1\,\mathrm{TeV}$ it leads to $\tau_V > \tau_{\mathrm{Universe}}$ for $\Lambda \gtrsim 10^{13}\,\mathrm{GeV}$

$m_V \simeq 1\,\mathrm{GeV}$ $\quad\quad\quad\quad$ $\Lambda \gtrsim 10^{9}\,\mathrm{GeV}$

Summary

If one tries to justify DM stability from gauge symmetry and particle content (as in the SM) a very simple non Z_2 possibility which emerges is by means of the custodial symmetry:

a hidden sector non-abelian gauge field with a scalar in the fundamental ← communicating with the SM through the Higgs portal

⇒ viable DM candidate within a large parameter range

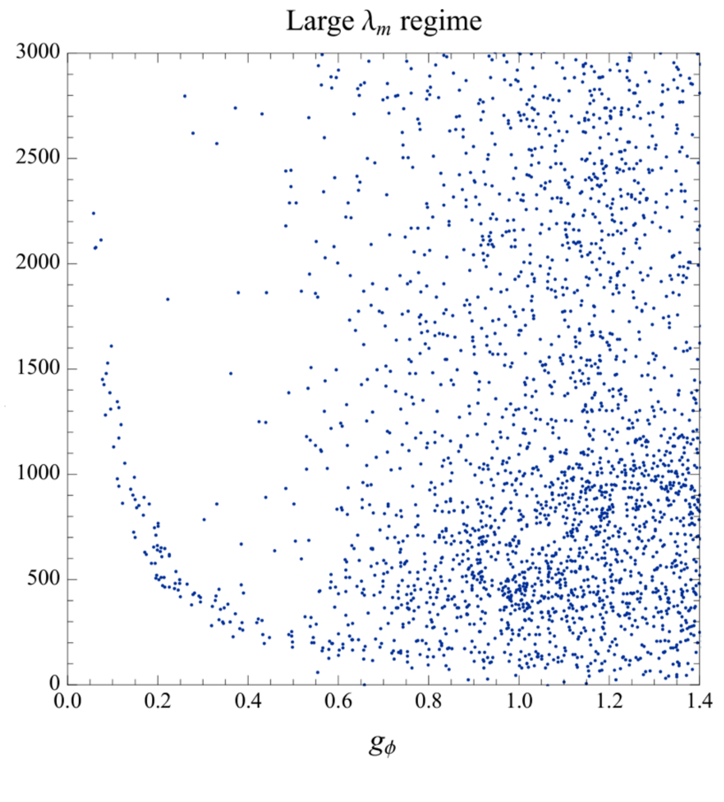
↪ either in the perturbative regime: DM = gauge bosons

$$1\,\mathrm{MeV} \lesssim m_{DM} \lesssim 50\,\mathrm{TeV}$$

↪ or in the confined regime: DM = vector boundstate in the adjoint

$$m_{DM} \simeq 20 - 200\,\mathrm{TeV}$$

⇒ rich phenomenology: direct detection, LHC (if $h-\eta$ mixing large), Pamela,...


Large λ_m regime
3000
2500
2000
1500
1000
500
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
g_ϕ