Perspectives for a WIMP discovery

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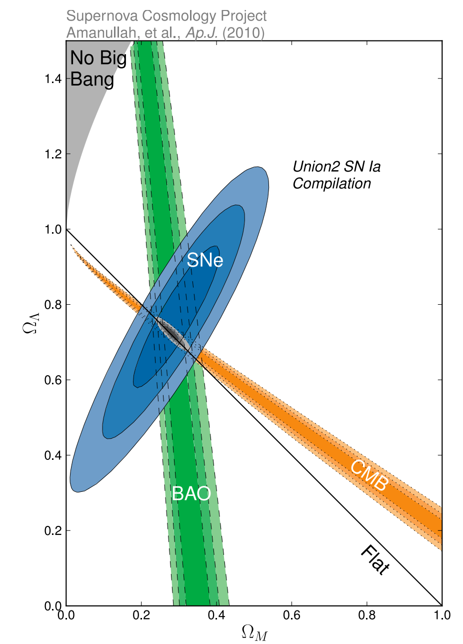
Gravitational evidences for dark matter

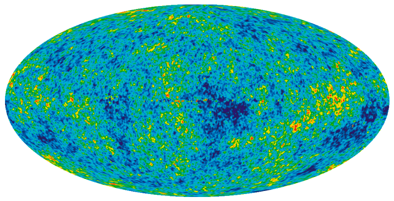
-At galactic scale: velocity distribution of stars

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

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

lead consistently to: $\Omega_{DM} \simeq 26\%$





DM is neutral, stable ($\tau_{DM} > 10^{26}\,\mathrm{sec}$), cold, $\Omega_{DM} \simeq 26\%$, has constrained cross section on Nucleon, produces constrained fluxes of cosmic rays, colliders, BBN, ...

but this still leaves an enormous freedom for the DM particle (mass, spin, interactions, stabilization mechanism, ...)

DM thermal relic density scenario (WIMP)

most straightforward way to explain $\Omega_{DM} \simeq 26\%$

If DM has been in thermal equilibrium with SM particles short after big bang

→ expected as soon as: - Universe thermal bath had a period with $T \sim m_{DM}$

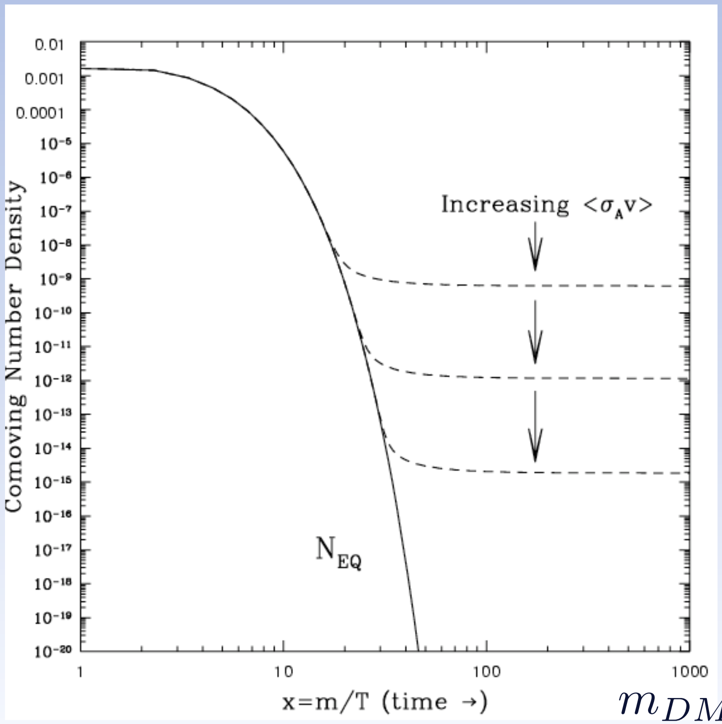
- SM-DM coupling not tiny ← $\lambda \gtrsim 10^{-7}$ for $m_{DM} \sim \text{TeV}$

$n_{DM}^{Eq.} \propto e^{-m_{DM}/T}$

→ cannot stay for long in thermal equilibr. once $T < m_{DM}$

→ once $\Gamma_{annih.} < H$: freeze out of DM particle number

$\frac{n_{DM}^{Eq}}{s}$



m_{DM}/T

⇒ $\Omega_{DM} \propto 1/\langle\sigma_{annih.}v\rangle$

→ $\Omega_{DM} \simeq 26\%$ requires $\langle\sigma_{annih.}v\rangle \simeq 10^{-26}\ \text{cm}^3/\text{sec}$

→ for electroweak couplings or couplings of order unity: $m_{DM} \sim \text{TeV}$

⇒ great perspectives of discovery

(Xenon1T, LZ, CTA, colliders, ...)

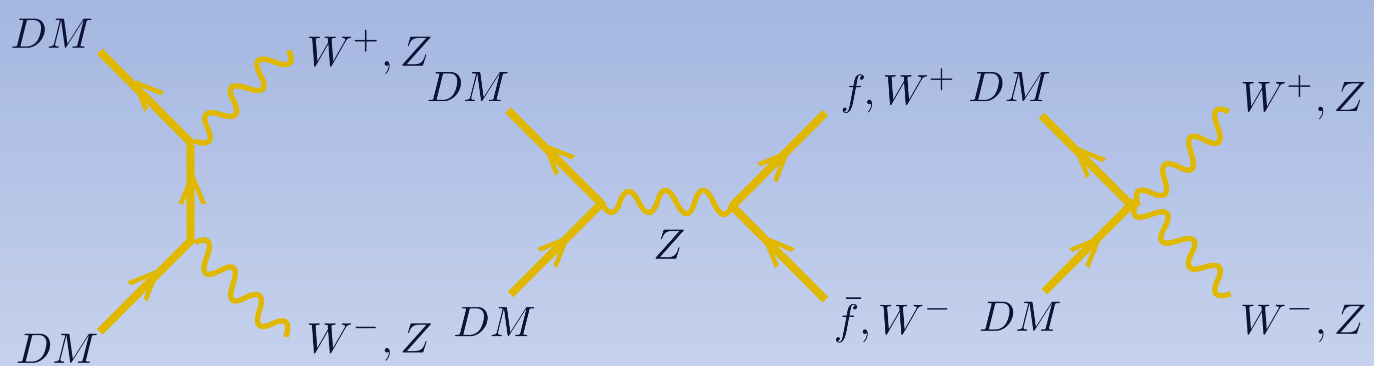
Most straightforward WIMP scale ~ TeV

examples: a fermion $SU(2)_L$ DM doublet ($Y_{DM} = 1/2$): $m_{DM} = 1.1\,\mathrm{TeV}$

a fermion $SU(2)_L$ DM triplet ($Y_{DM} = 0$): $m_{DM} = 3.1\,\mathrm{TeV}$

a scalar $SU(2)_L$ DM doublet ($Y_{DM} = 1/2$): $m_{DM} \geq 540\,\mathrm{GeV}$

a scalar $SU(2)_L$ DM triplet ($Y_{DM} = 0$): $m_{DM} \geq 2.5\,\mathrm{TeV}$



see e.g. *Cirelli, Strumia et al.* '07

⇒ around the corner! ← (but not necessarily at LHC!)

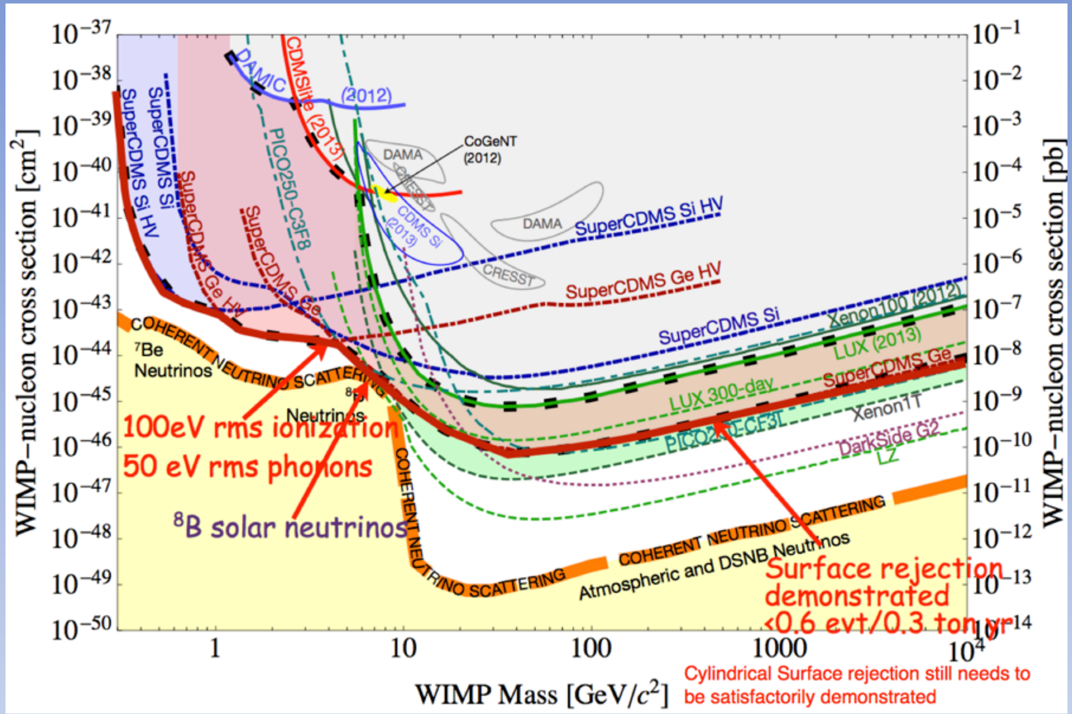
WIMP scale could also be lower or higher

if driven by larger couplings up to ~100 TeV: unitarity bound

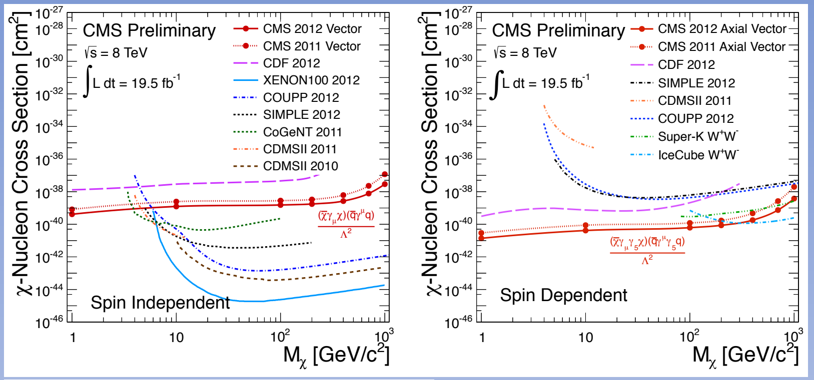
if Fermi suppression, or driven by smaller couplings, or interplay of channels, or small mass splittings, ...

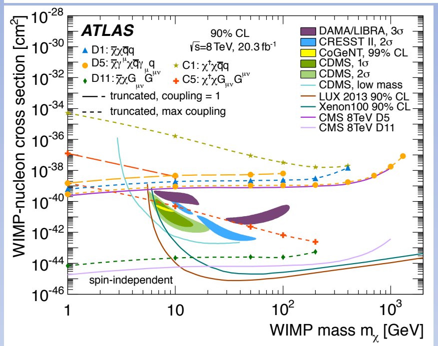
DM search: 3 main types of experiments

Direct detection: DM-N collision:



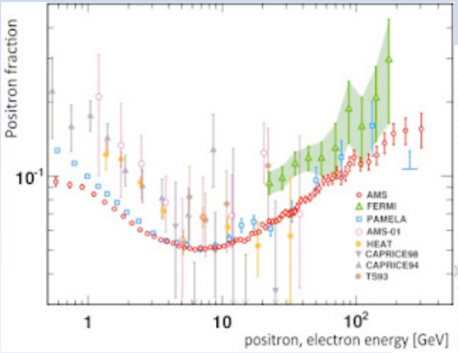
Colliders: DM pair production:

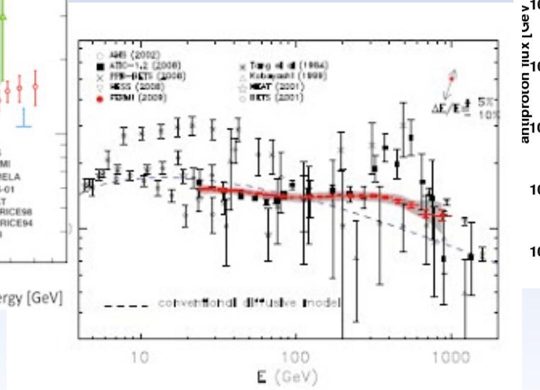


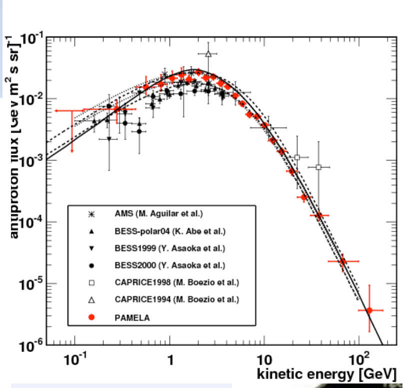


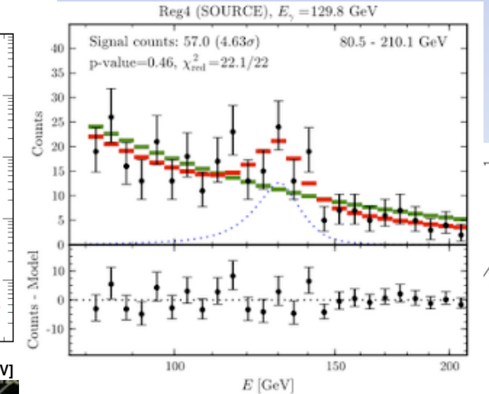
Monojets,
monophoton,
monoW/Z,
cascade decays,
....

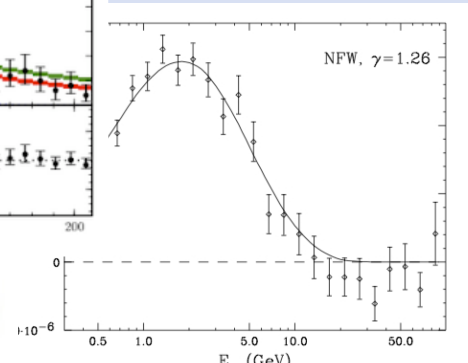
Indirect detection: cosmic rays from DM annihilation or decay:











3 main types of phenomenological approaches

Effective operators: most model independent approach

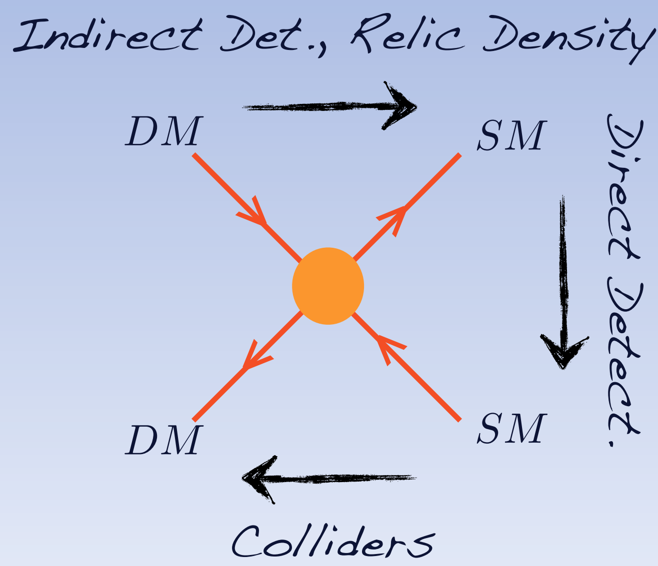
Explicit DM-SM mediator setups

Explicit DM models

Effective operator approach

from determining and analysing the full series of effective operators quadratic in the DM field (or linear for a DM decay)

is well justified for DM direct and indirect detection, not necessarily for collider studies



Effective oper. approach: fermion dark matter coupled to quarks

examples: vector and axial operators

$$\mathcal{O} = \frac{1}{\Lambda^2}\bar{\psi}_{DM}\gamma_\mu\psi_{DM}\,\bar{q}\,\gamma^\mu q$$

spin-independent direct detect.

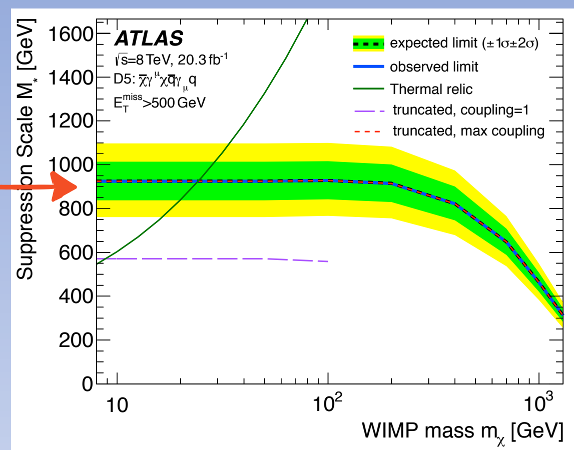
$$\mathcal{O} = \frac{1}{\Lambda^2}\bar{\psi}_{DM}\gamma_\mu\gamma_5\psi_{DM}\,\bar{q}\,\gamma^\mu\gamma_5 q$$

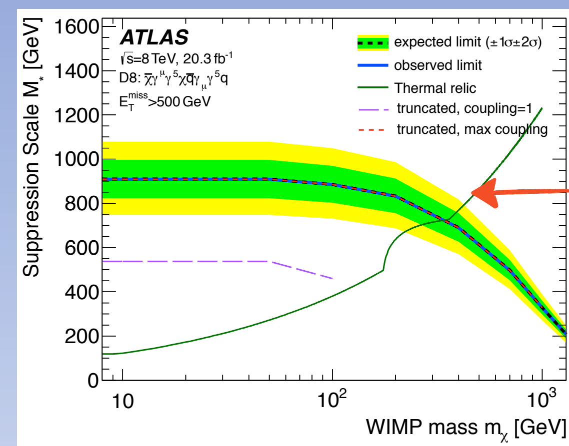
spin-dependent direct detect.

Colliders: $\Lambda \gtrsim 1\,\mathrm{TeV}$

for m_{DM} up to $\sim 500\,\mathrm{GeV}$

from monojets, mono-photon, mono-W, ...





Colliders: $\Lambda \gtrsim 1\,\mathrm{TeV}$

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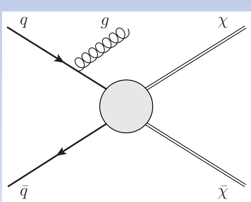
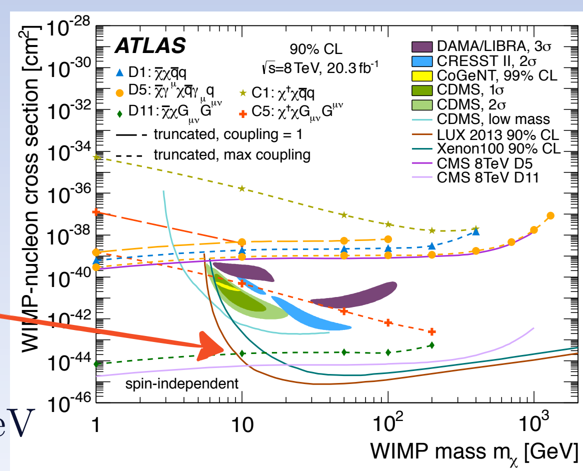
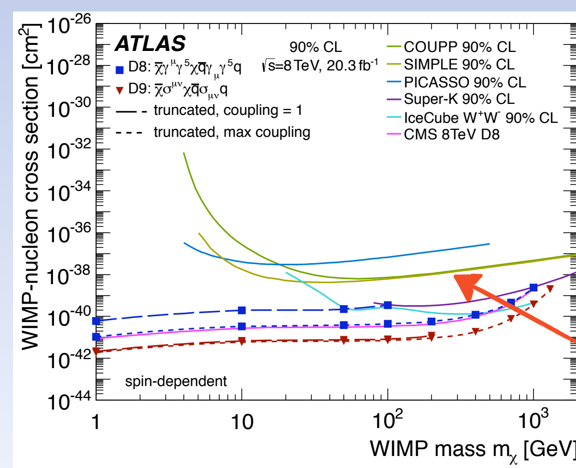






Direct Detect.:

$\Lambda \gtrsim 10\,\mathrm{TeV}$

for $10\,\mathrm{GeV} \gtrsim m_{DM} \gtrsim 1\,\mathrm{TeV}$

Direct Detect.:

$\Lambda \gtrsim 600\,\mathrm{GeV}$

$10\,\mathrm{GeV} \gtrsim m_{DM} \gtrsim 1\,\mathrm{TeV}$

N.B.: Xenon1T will probe Λ effective scale values up to 3-4 times higher!

Effective oper. approach: fermion dark matter coupled to SM scalar

examples: parity even and odd operators

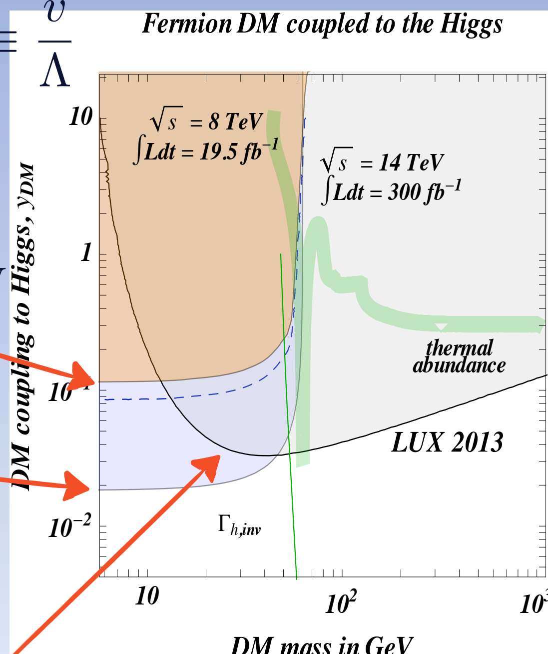
$$\mathcal{O} = \frac{1}{\Lambda} H^\dagger H \, \bar{\psi}_{DM} \psi_{DM}$$

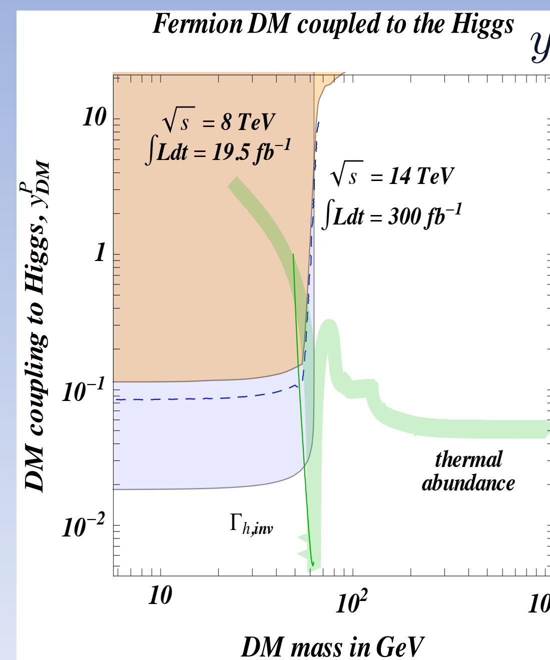
spin-independent direct detect.

$$\mathcal{O} = \frac{1}{\Lambda} H^\dagger H \, \bar{\psi}_{DM} i\gamma_5 \psi_{DM}$$

spin-dependent direct detect.

$$y_{DM} \equiv \frac{v}{\Lambda}$$





$$y_{DM} \equiv \frac{v}{\Lambda}$$

LHC monojets
for m_{DM} up to $\sim 60\,\mathrm{GeV}$

LHC: Higgs boson invisible decay width

Direct Detect.:
$\Lambda \gtrsim 10\,\mathrm{TeV}$
for $10\,\mathrm{GeV} \gtrsim m_{DM} \gtrsim 1\,\mathrm{TeV}$

....
Lopez-Honorez, Schwetz, Zupan 12
De Simone, Giudice, Strumia 14
....

Direct Detect.:
no relevant bound

Systematic study of effective theory for γ-line production from DM decay

- γ-line: no astrophysics background → DM "smoking gun"
  - → promising experiments: Fermi, HESS-2, CTA, ...

$\tau_{DM} > \tau_{Universe}$

$\tau_{DM} > 10^{26-29}$ sec

- one perfectly possible scenario: γ-lines from radiative 2-body DM decay
  - → e.g. if DM is stable due to accidental sym. as for the proton
    - ↓ very slow decay can be expected as for the proton from UV physics inducing low energy effect. operators

a GUT induced dim-6 operator gives cosmic ray fluxes of order experimental sensitivity!

Gustafsson, T.H., Scarna 13

for a scalar DM candidate:

$$O^{(5)YY}_{\phi_{DM}} \equiv \phi_{DM} F_{Y\mu\nu} F^{\mu\nu}_{Y} \qquad \phi_{DM} = (1,0)$$
$$O^{(5)YL}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F^{\mu\nu}_{Y} \qquad \phi_{DM} = (3,0)$$
$$O^{(5)LL}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F^{\mu\nu}_{L} \qquad \phi_{DM} = (1/3/5,0)$$
$$O^{(5)YY'}_{\phi_{DM}} \equiv \phi_{DM} F_{Y\mu\nu} F^{\mu\nu}_{Y'} \qquad \phi_{DM} = (1,0)$$
$$O^{(5)LY'}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F^{\mu\nu}_{Y'} \qquad \phi_{DM} = (3,0)$$

$$O^{1YY}_{\phi_{DM}} \equiv \phi_{DM} F_{Y\mu\nu} F^{\mu\nu}_{Y} \phi \qquad \phi_{DM} \cdot \phi = (1,0)$$
$$O^{1YL}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F^{\mu\nu}_{Y} \phi \qquad \phi_{DM} \cdot \phi = (3,0)$$
$$O^{1LL}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F^{\mu\nu}_{L} \phi \qquad \phi_{DM} \cdot \phi = (1/3/5,0)$$
$$O^{1YY'}_{\phi_{DM}} \equiv \phi_{DM} F_{Y\mu\nu} F^{\mu\nu}_{Y'} \phi \qquad \phi_{DM} \cdot \phi = (1,0)$$
$$O^{1LY'}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F^{\mu\nu}_{Y'} \phi \qquad \phi_{DM} \cdot \phi = (3,0)$$
$$O^{2Y}_{\phi_{DM}} \equiv D_\mu \phi_{DM} D_\nu \phi F^{\mu\nu}_{Y} \qquad \phi_{DM} \cdot \phi = (1,0)$$
$$O^{2L}_{\phi_{DM}} \equiv D_\mu \phi_{DM} D_\nu \phi F^{\mu\nu}_{L} \qquad \phi_{DM} \cdot \phi = (3,0)$$

for a fermion DM candidate:

$$O^{(5)Y}_{\psi_{DM}} \equiv \bar{\psi} \sigma_{\mu\nu} \psi_{DM} F^{\mu\nu}_{Y} \qquad \psi_{DM} \cdot \psi = (1,0)$$
$$O^{(5)L}_{\psi_{DM}} \equiv \bar{\psi} \sigma_{\mu\nu} \psi_{DM} F^{\mu\nu}_{L} \qquad \psi_{DM} \cdot \psi = (3,0)$$

$$O^{1Y}_{\psi_{DM}} \equiv \bar{\psi} \sigma_{\mu\nu} \psi_{DM} F^{\mu\nu}_{Y} \phi \qquad \bar{\psi} \cdot \psi_{DM} \cdot \phi = (1,0)$$
$$O^{1L}_{\psi_{DM}} \equiv \bar{\psi} \sigma_{\mu\nu} \psi_{DM} F^{\mu\nu}_{L} \phi \qquad \bar{\psi} \cdot \psi_{DM} \cdot \phi = (3,0)$$
$$O^{2Y}_{\psi_{DM}} \equiv D_\mu \bar{\psi} \gamma_\nu \psi_{DM} F^{\mu\nu}_{Y} \qquad \bar{\psi} \cdot \psi_{DM} = (1,0)$$
$$O^{2L}_{\psi_{DM}} \equiv D_\mu \bar{\psi} \gamma_\nu \psi_{DM} F^{\mu\nu}_{L} \qquad \bar{\psi} \cdot \psi_{DM} = (3,0)$$
$$O^{3Y}_{\psi_{DM}} \equiv \bar{\psi} \gamma_\mu D_\nu \psi_{DM} F^{\mu\nu}_{Y} \qquad \bar{\psi} \cdot \psi_{DM} = (1,0)$$
$$O^{3L}_{\psi_{DM}} \equiv \bar{\psi} \gamma_\mu D_\nu \psi_{DM} F^{\mu\nu}_{L} \qquad \bar{\psi} \cdot \psi_{DM} = (3,0)$$

for a spin-1 DM candidate:

$$O^{(5)Y}_{V_{DM}} \equiv F^{DM}_{\mu\nu} F^{\mu\nu}_{Y} \phi \qquad \phi = (1,0)$$
$$O^{(5)L}_{V_{DM}} \equiv F^{DM}_{\mu\nu} F^{\mu\nu}_{L} \phi \qquad \phi = (3,0)$$

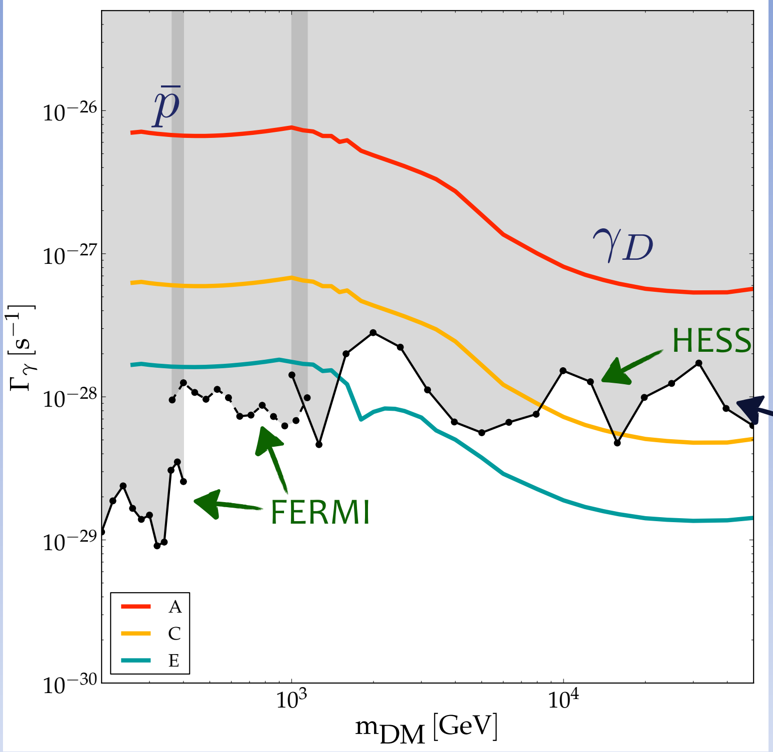
$$O^{1}_{V_{DM}} \equiv F^{DM}_{\mu\nu} F^{\mu\rho}_{Y} F^{\nu}_{Y'\rho}$$
$$O^{2Y}_{V_{DM}} \equiv F^{DM}_{\mu\nu} F^{\mu\nu}_{Y} \phi\phi' \qquad \phi \cdot \phi' = (1,0)$$
$$O^{2L}_{V_{DM}} \equiv F^{DM}_{\mu\nu} F^{\mu\nu}_{L} \phi\phi' \qquad \phi \cdot \phi' = (3,0)$$
$$O^{3YY'}_{V_{DM}} \equiv D^{DM}_{\mu} \phi D^{DM}_{\nu} \phi' F^{\mu\nu}_{Y} \qquad \phi \cdot \phi' = (1,0)$$
$$O^{3LY'}_{V_{DM}} \equiv D^{DM}_{\mu} \phi D^{DM}_{\nu} \phi' F^{\mu\nu}_{L} \qquad \phi \cdot \phi' = (3,0)$$

Upper bounds on γ-line intensity from DM decay

A $DM \to \gamma + X$ decay comes with a $DM \to Z + X$ decay (and $DM \to W + X'$)

$\Rightarrow$ unavoidable production of cosmic rays

$\Rightarrow$ bound on γ-line intensity from bounds on cosmic ray fluxes



Gustafsson, T.H., Scarna 13

upper bounds depen-ding on operator

direct γ-line search

possibilities of operator discrimination ← combined with the fact that op. can give more than one line

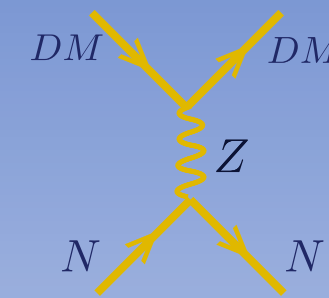
N.B.: an observable γ-line could also be due to the possible fact that the DM particle is not absolutely neutral

El Asaiti, T.H., Scarna 14 → DM millicharge

Explicit mediator approach: Z mediator for fermion DM

e.g. assuming DM/SM specific mediator:

- Z mediator: fermion DM: vector and axial DM coupling to the Z



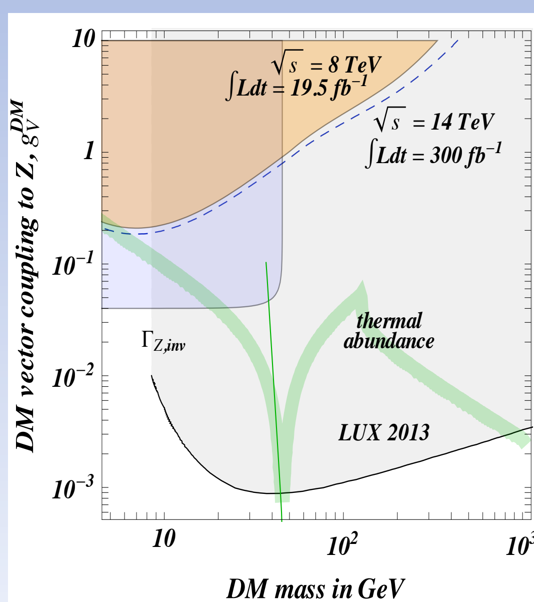
$$\mathcal{L} \ni -Z_\mu \frac{g}{\cos\theta_W} \bar{\psi}_{DM}(g_V^{DM} + g_A^{DM}\gamma_5)\gamma^\mu \psi_{DM}$$

For direct detection: the Z can be integrated out → same discussion than with effective operators

$$\frac{1}{\Lambda} \sim \frac{g_{V,A}^{DM}}{m_Z} \frac{g}{\cos\theta_W}$$

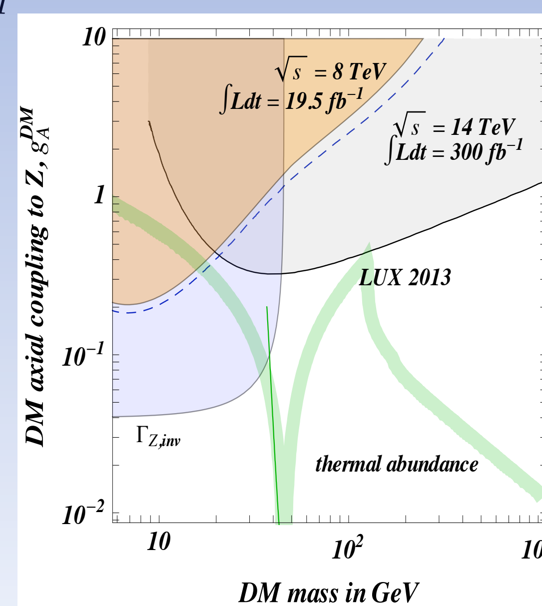
For colliders: the Z must be kept explicit

g_V^{DM}



↓ totally excluded for "standard" Z couplings

g_A^{DM}



↓ still largely open for $m_{DM} > 60\,\text{GeV}$

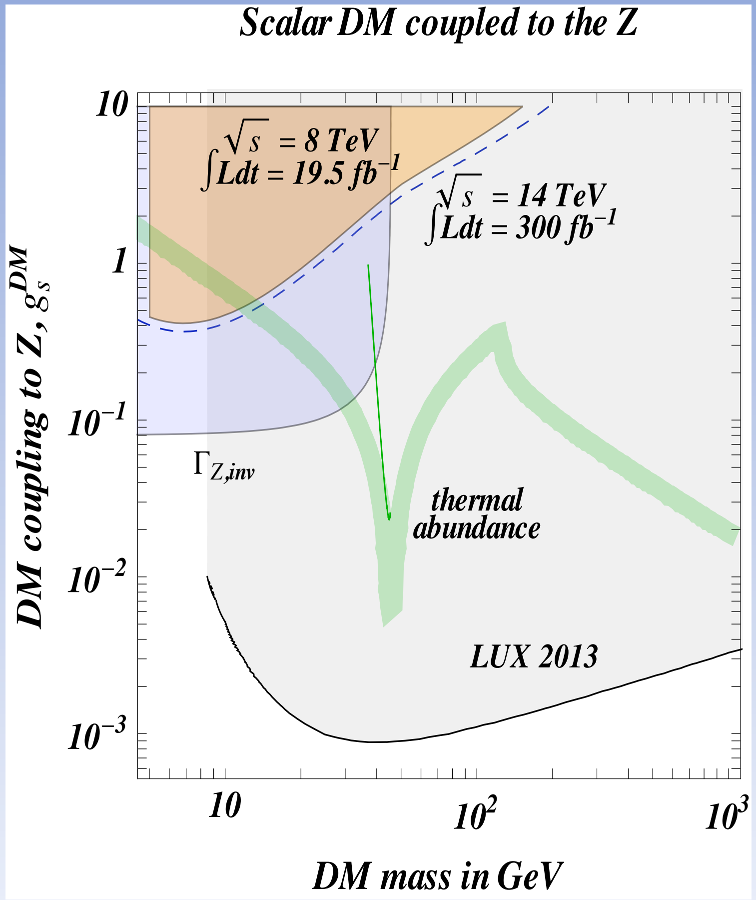
De Simone, Giudice, Strumia 14

....

Explicit mediator approach: Z mediator for scalar DM

$$\mathcal{L} \ni -Z_\mu \frac{g}{\cos\theta_W} g_\phi \left[\phi^*_{DM}\partial^\mu\phi_{DM} - \partial^\mu\phi^*_{DM}\phi_{DM}\right]$$

similar to fermion DM vector case



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totally excluded for "standard" Z couplings

Explicit mediator approach: SM scalar mediator

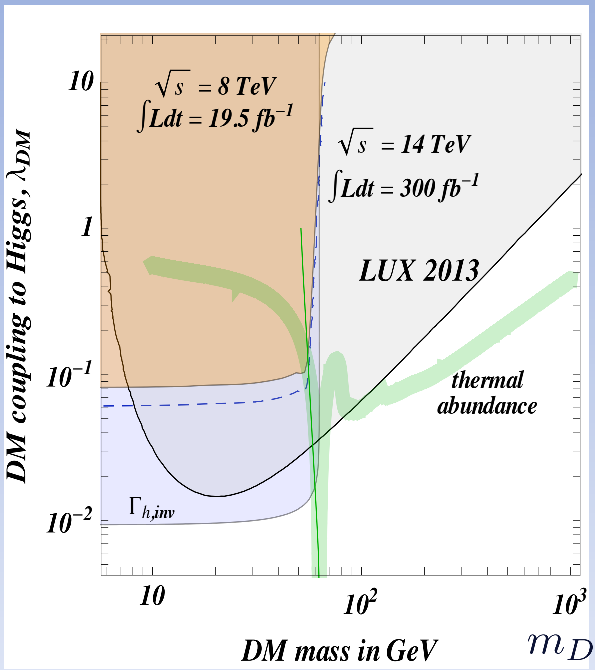
- Fermion DM: lowest gauge invariant interaction: dim-5 ⇒ back to effective oper. discussion

$$\mathcal{O} = \frac{1}{\Lambda} H^\dagger H \; \bar{\psi}_{DM} \psi_{DM}$$

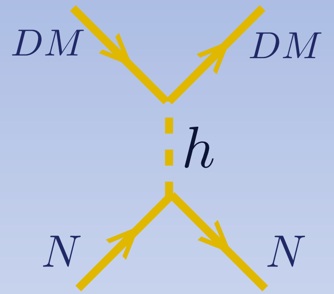
- Scalar DM: Higgs portal interaction: $\mathcal{L} \ni \lambda_{DM} H^\dagger H \, \phi^*_{DM} \phi_{DM}$

De Simone, Giudice, Strumia 14

λ_{DM}



m_{DM} (GeV)



⇓

begin to be pretty much constrained below $100\,\mathrm{GeV}$

N.B.: Xenon1T will probe it up to $\sim 10\,\mathrm{TeV}$ for $\lambda_{DM} \sim 1$

up to $\sim 1\,\mathrm{TeV}$ for $\lambda_{DM} \sim 10^{-1}$

BSM mediator: the Z' example

Much less constrained: mass and couplings of mediator unknown

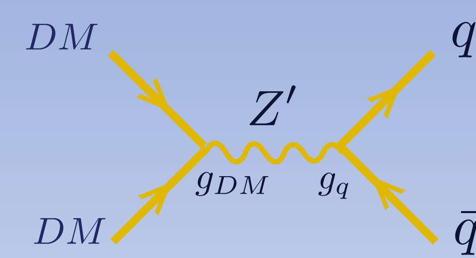
- bounds relax if mediator couplings to SM fields are smaller than for Z
- bounds relax if mediator mass increases

↪ example: a fermion DM coupling to SM fermion through a Z' :

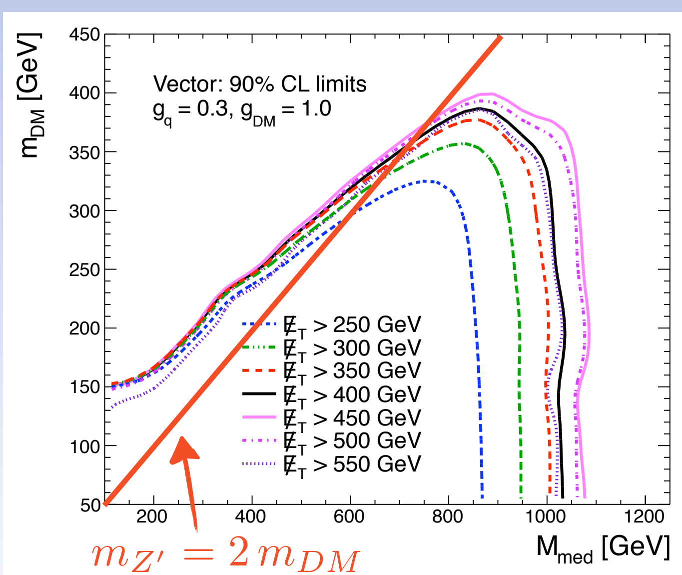
⇓

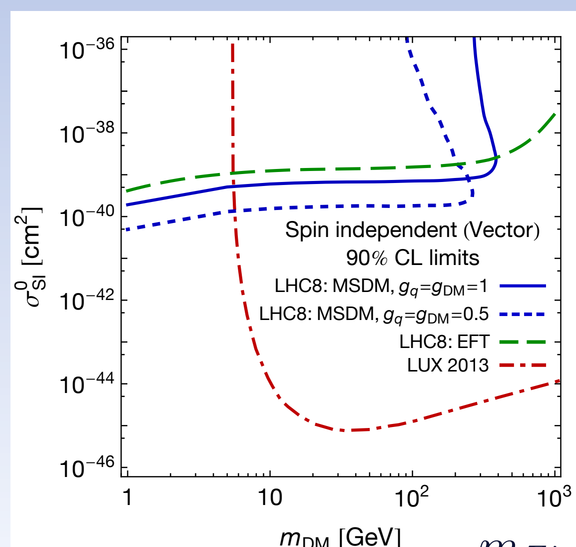
5 parameters:

$$m_{DM},\ m_{Z'},\ g_{DM},\ g_q,\ \Gamma_{Z'}$$

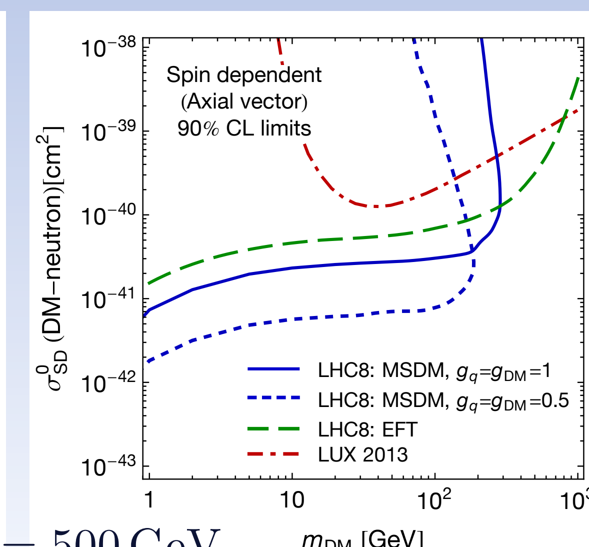


O. Buchmueller, Dolan, Malik, Mc Cabe 15'



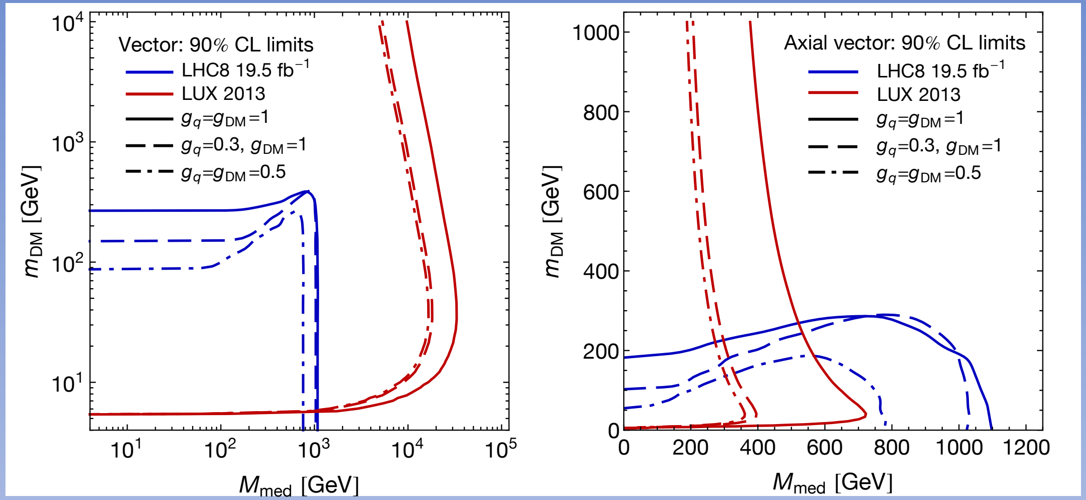


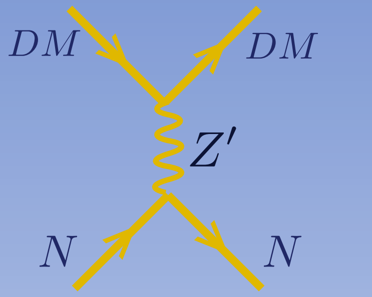
$m_{Z'} = 500\,\mathrm{GeV}$



Z' mediator

O. Buchmueller, Dolan, Malik, Mc Cabe 15'

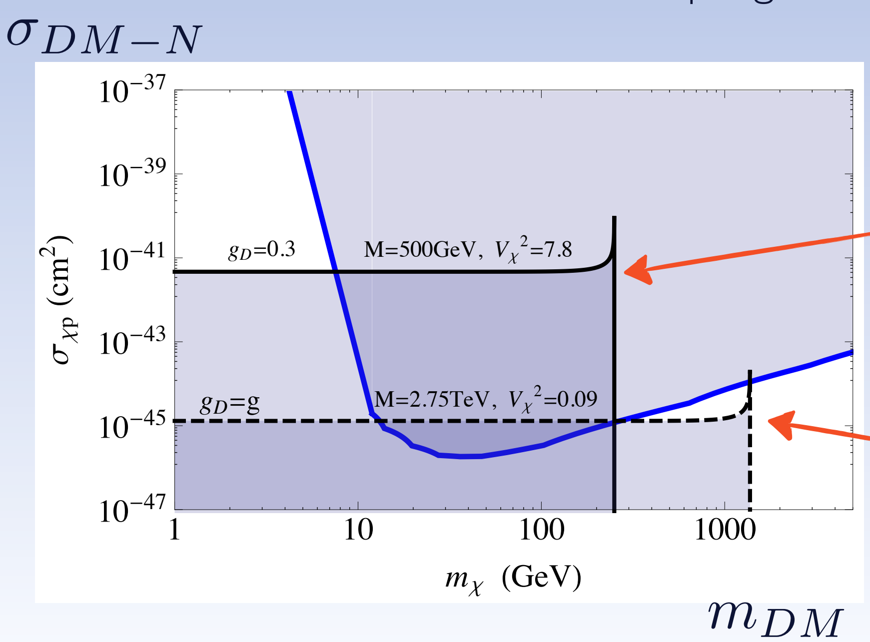




Direct detection: put an upper bound on Z'-DM couplings

LHC Z' direct search: put a lower bound on Z'-DM couplings

to escape Z' detection via large invisible Z' decay width



LHC direct search $m_{Z'} = 500\,\mathrm{GeV}$

LUX

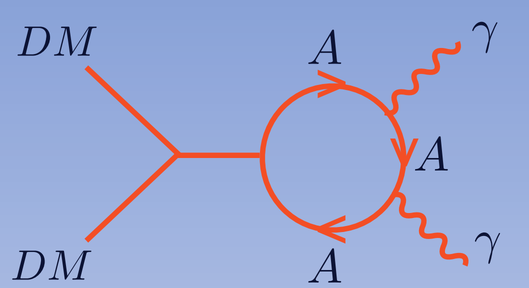
LHC direct search $m_{Z'} = 2.75\,\mathrm{TeV}$

Arcadi, Mambrini, Tytgat, Zaldivar 14

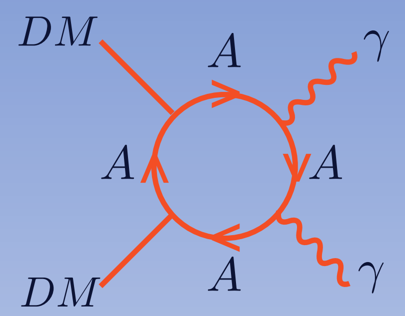
Mediator for γ-lines and "gluon-lines"

- γ-line emission production proceeds through photon emission from a charged particle in a loop

as for well known examples: $h \to \gamma\gamma,\ \pi^0 \to \gamma\gamma, \ldots$

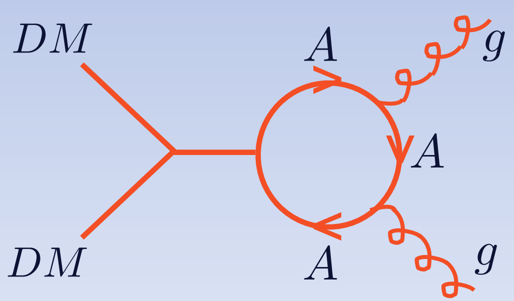


$\Longleftrightarrow$

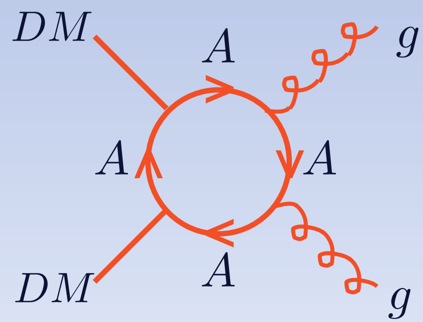


if the charged particle emitting the γ-line is also colored: "gluon lines":

as for well known examples: $h \to \gamma\gamma,\ \pi^0 \to \gamma\gamma, \ldots$



$\Longleftrightarrow$



Chu, T.H., Scarna, Tytgat 12

$$R = \frac{n_g}{n_\gamma}$$

depends on $SU(3)_c$ representation for A

is basically known: $R \propto \frac{\alpha_s^2}{\alpha^2} \cdot \frac{c}{Q_A^4} \sim 50 - 100$

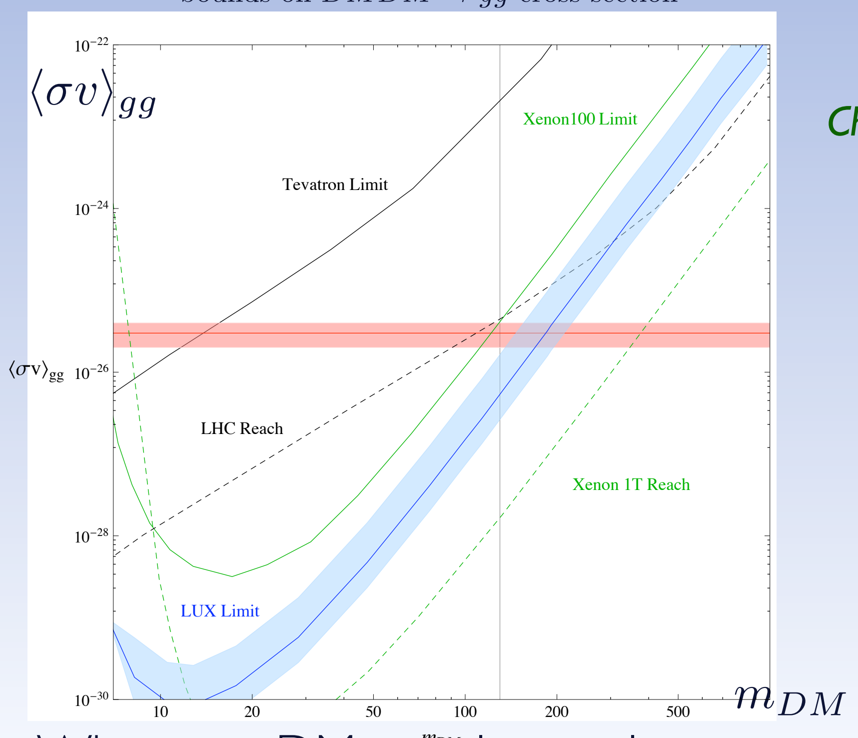
$\Rightarrow$ many experimental consequences!

“Gluon lines” associated to γ-lines

Many experimental consequences!

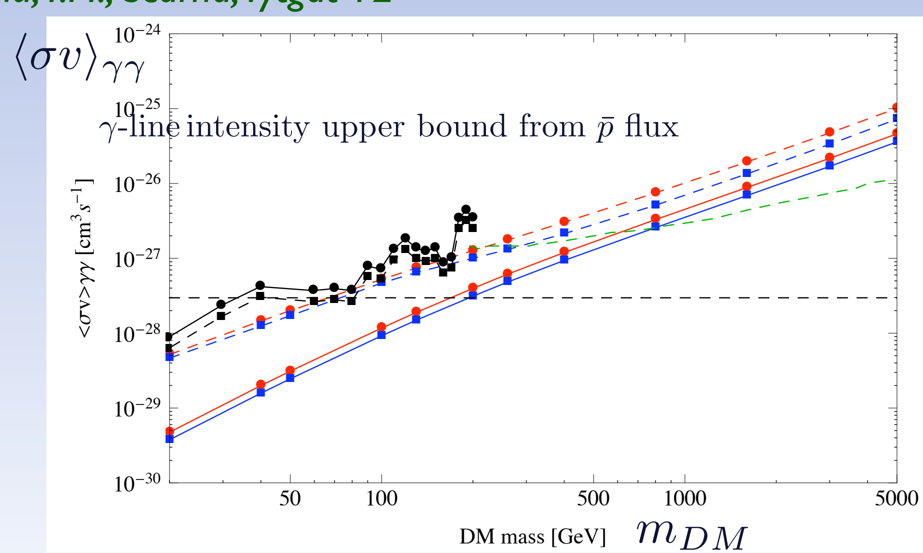
- gluon “lines” may lead to observable $\bar{p}$ flux for $m_{DM} \sim$ few hundreds GeV
- gluon “lines” may lead to observable γ continuum flux
- gluon exchange leads to DM-$Nucleon$ cross section: observable for $m_{DM} \lesssim 500\,\mathrm{GeV}$
- possibility of gluon fusion DM pair production at LHC
- gluon “lines” production gives a DM annihilation cross section of the right order of magnitude for fitting observed relic density

direct detection and collider upper bounds on $DMDM \to gg$ cross section



for a γ-line observed around current experimental sensitivity

Chu, T.H., Scarna, Tytgat 12



Whenever DM couples to gluon: many experimental possibilities!

Explicit models

DM models can be classified according to various criteria:

Minimal models	→ ←	More theoretically motivated global models
Visible sector DM models	→ ←	Hidden sector DM models
ad hoc DM stability	→ ←	justified DM stability

$$\tau_{DM} > \tau_{Universe}$$

$$\tau_{DM} > 10^{26-29}\,\mathrm{sec}$$

The stabilization mechanism determines many structural features of the all DM scenario

DM/EW scale similarity just so	→ ←	DM/EW scale similarity explained

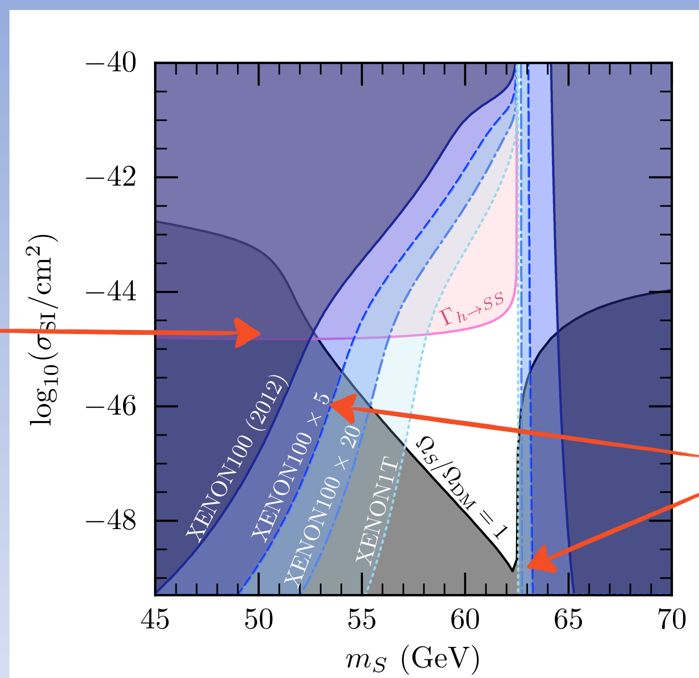
Explicit models: the simplest example: a real scalar singlet

a real singlet S odd under Z_2 parity: $S \to -S$

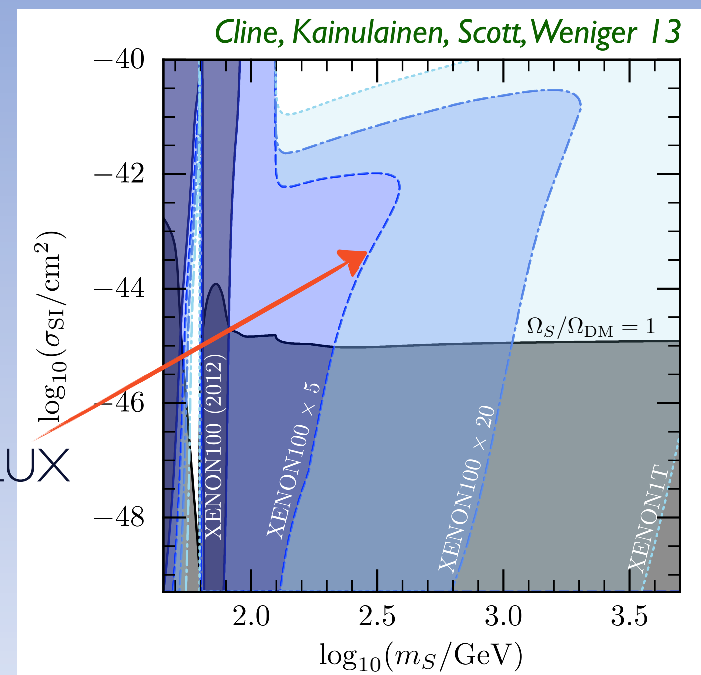
$$\mathcal{L} \ni -\frac{1}{2}\mu_S^2 S^2 - \frac{1}{24}\lambda_S S^4 - \frac{1}{2}\lambda_{hs} H^\dagger H S^2 \qquad m_S^2 = \mu_S^2 + \frac{1}{2}\lambda_{hs} v^2$$

For m_S fixed, λ_{hs} can be fixed by $\Omega_{DM} \simeq 26\%$ constraint: everything is fixed!

Higgs invisible width



~ LUX



LUX direct detection requires: $53\,\mathrm{GeV} \lesssim m_{DM} \lesssim 63\,\mathrm{GeV}$
or $m_{DM} > 160\,\mathrm{GeV}$

Dwarf galaxies γ-ray flux requires: $m_{DM} \gtrsim 50\,\mathrm{GeV}$

Future: Xenon1T will probe m_{DM} up to $7\,\mathrm{TeV}$
except for: $55\,\mathrm{GeV} \lesssim m_{DM} \lesssim 62.5\,\mathrm{GeV}$

Fermi+CTA will probe m_{DM} up to $5\,\mathrm{TeV}$

⇒ shows how a model is getting very squeezed when it depends on only very few parameters

Explicit models: the illustrative Wino example

e.g. a fermion $SU(2)_L$ triplet DM

have only gauge interactions with SM fields:
relic density totally fixed by value of m_{DM}

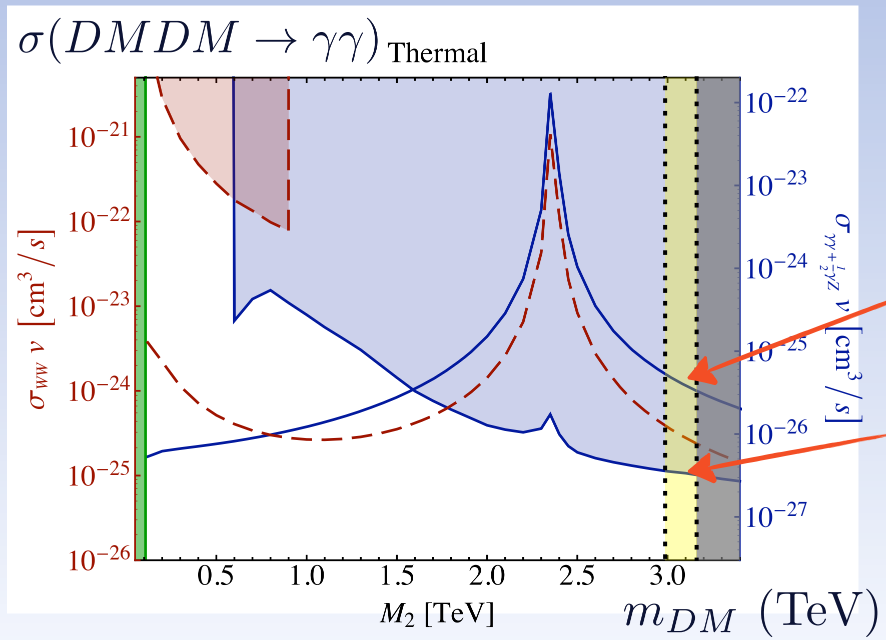
$\Omega_{DM} \simeq 26\%$ requires $m_{DM} \simeq 3.1\,\mathrm{TeV}$

too high for LHC
direct detection: $\sigma_{DM-N} \simeq 10^{-47}\,\mathrm{cm}^2$
far future: Darwin?

But Indirect detection remains!! → production of γ-line is Sommerfeld enhanced

Hisano et al. 03-09

Cohen, Lisanti, Pierce, Slatyer 13



⇒ we should soon see a signal
or exclude this model!

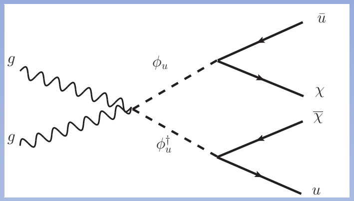
Explicit models: DM coupled to a colored partner

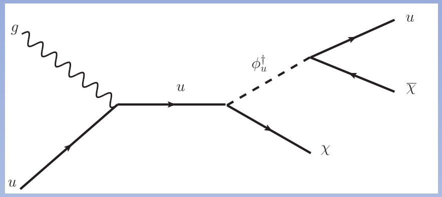
→ many proposals to couple DM directly to a colored partner

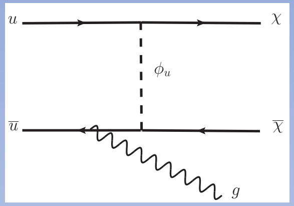
- Example: $\mathcal{L} \ni \lambda_u \, \bar{\chi}_{DM} \, u_R \, \phi_c$ *Bai, Berger 13*

  → scalar colored triplet

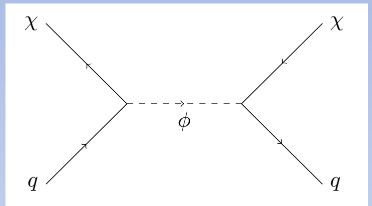
→ many ways to produce DM at colliders in unsuppressed way

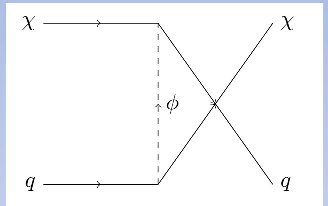






→ unsuppressed direct detection in s channel

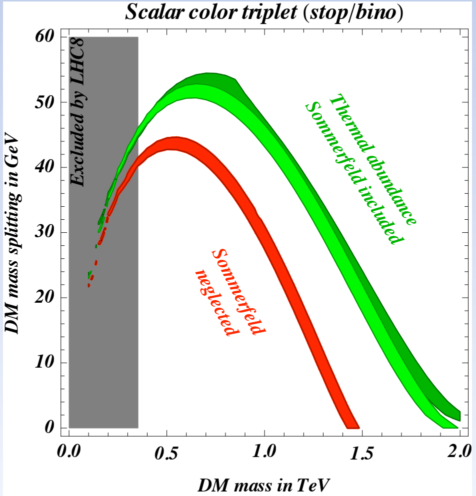




- DM coannihilation with a color partner

  → example: bino in thermal equilibrium with a stop or a gluino

  De Simone, Giudice, Strumia 14



- ...

"Hand-made" to be testable at LHC rather than for any other reason

Explicit models: MSSM neutralino

- Main impact of the LHC on MSSM: colored sector: $m_{\tilde{g}} \gtrsim 1\,\mathrm{TeV}$

  $m_{\tilde{u},\tilde{d}} \gtrsim 1\,\mathrm{TeV}$

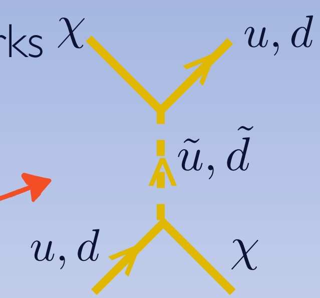
  → leaves neutralino option widely open

  → impact of gluino mass bound on neutralino parameters is mild

  → impact of 1st generat. squarks mass bounds on neutralino parameters is also mild

  e.g. can suppress various quarks exchange diagrams:

  DM direct detection →



- Impact of $m_h = 125.3 \pm 0.6\,\mathrm{GeV}$:

  one stop should be heavy: has the tendancy to push Higgsino mass above $\sim 500\,\mathrm{GeV}$

  through RGE's

  ⇒ if $m_\chi \lesssim 500\,\mathrm{GeV}$ neutralino easier it is Bino dominated

  → widely allowed experimentally

  a neutralino as light as ~20-30 GeV is still possible (in fully general MSSM) *Calibbi et al 12*

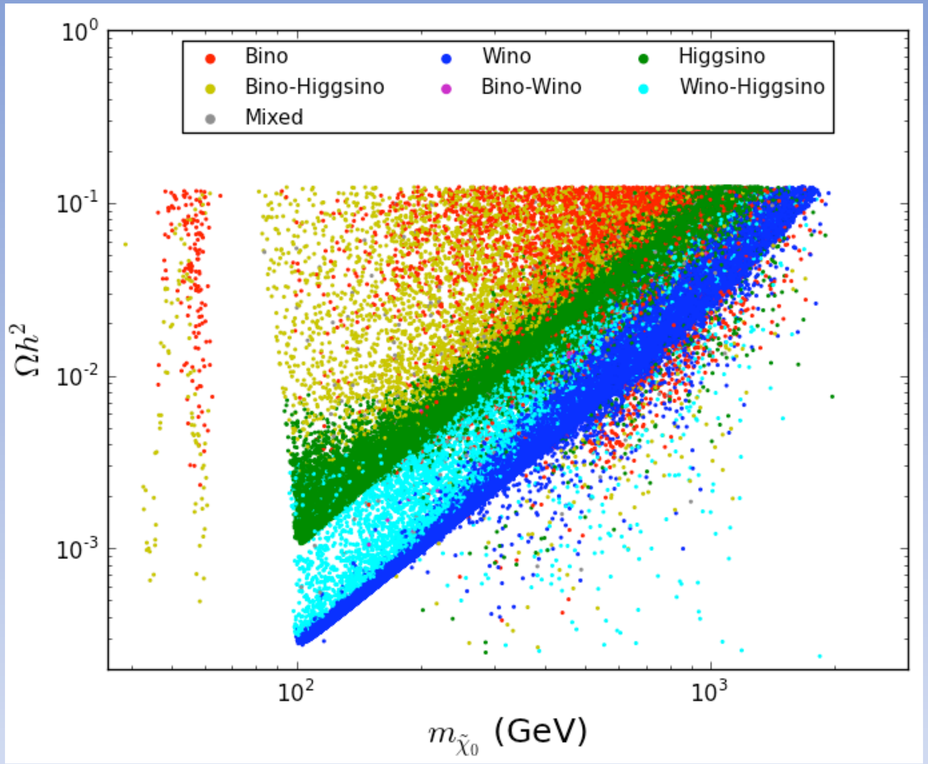
  if $m_\chi \gtrsim 500\,\mathrm{GeV}$ neutralino can be easily Higgsino dominated

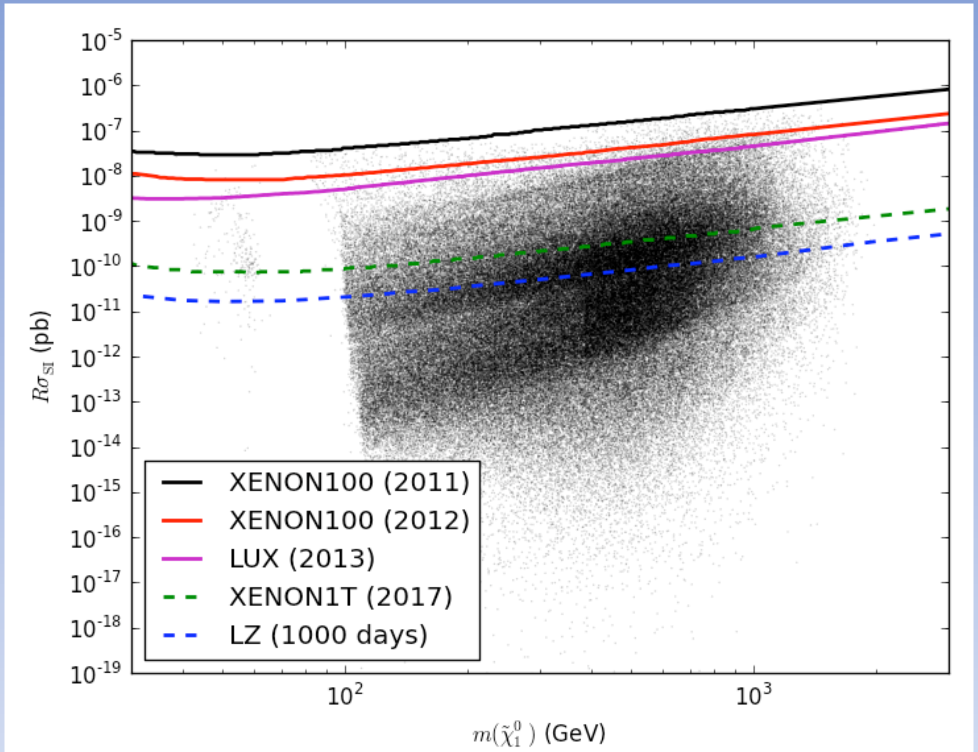
  if neutralino is Wino dominated its mass must be $m_\chi \sim 3\,\mathrm{TeV}$

Explicit models: MSSM neutralino

$pMSSM$ (19 parameters)

Rizzo 14, ...





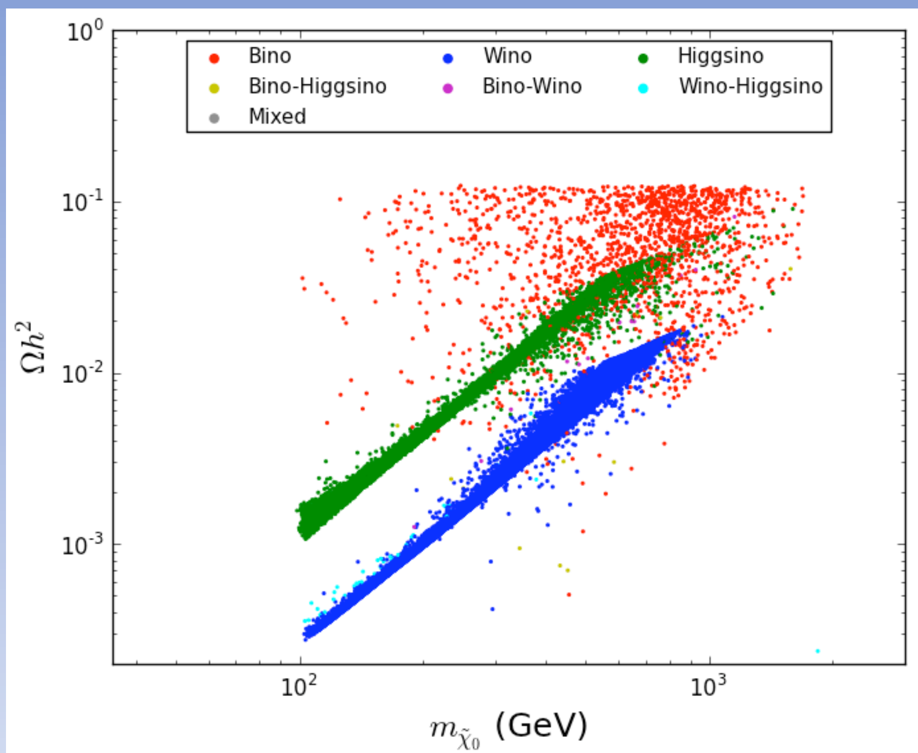
relic density point out a neutralino below ~3 TeV (i.e. gauge driven, or loop driven, ...) but could be higher

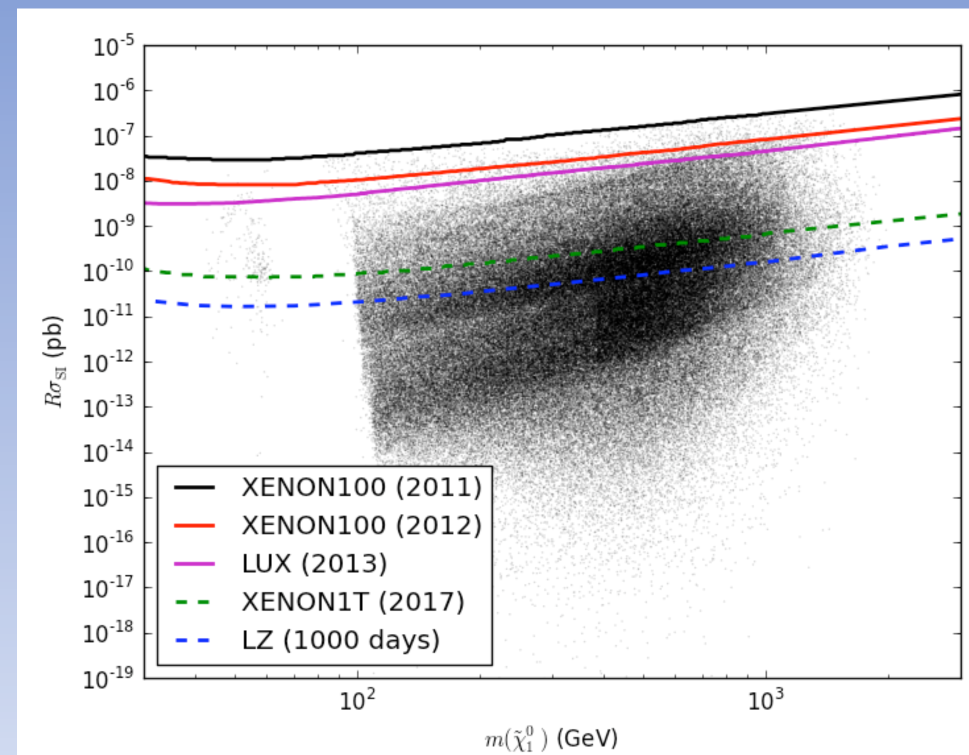
still not much probed by direct detection but Xenon1T, LZ, ..., will probe it substantially

Explicit models: MSSM neutralino

$pMSSM$ (19 parameters)

Rizzo 14, ...





e.g. bino with coannihilation or resonance can still saturate the observed Ω_{DM}

still not much probed by direct detection but Xenon1T, LZ, ..., will probe it substantially

example of multichannel model with good experimental perspective (but no guarantee)

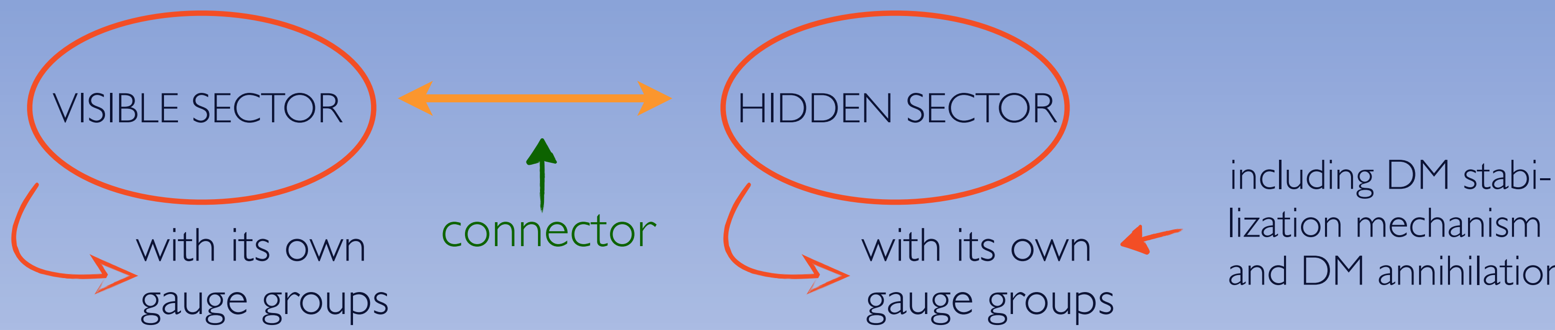
Explicit models: Hidden sector models

DM could be part of an all hidden sector

....

"Secluded DM" *Pospelov, Ritz, Voloshin 07*

....



Testability depends on connector size: no more LHC, Direct/Indirect Detect., as soon as the connector coupling is sizably below unity

↓

only gravitational probes remain:

- extra radiation constraint
- DM self-interaction constraints (halo formation, bullet cluster,...)
- BBN, ...

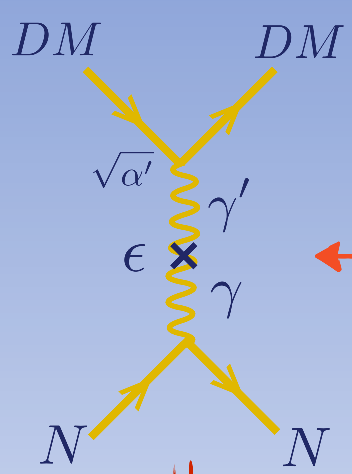
Berezhiani, Comelli, Villante 01
Feng, Tu, Yu 08
Ackerman, Buckley, Carroll, Kamionkowski, 09
Feng, Kaplinghat, Tu, Yu 09
Berezhiani, Lepidi 09
Mc Dermott, Yu, Zurek 10 , ...

Explicit models: Hidden sector models with light connector

Simple example:

$$\mathcal{L} \ni -\frac{1}{4} F'_{\mu\nu} F_Y^{\mu\nu}$$

a DM fermion charged under an unbroken U(1) which kinetically mixes with the photon



$$\frac{1}{q^2} \rightarrow \frac{1}{E_r^2}$$

$E_r \sim$ few KeV

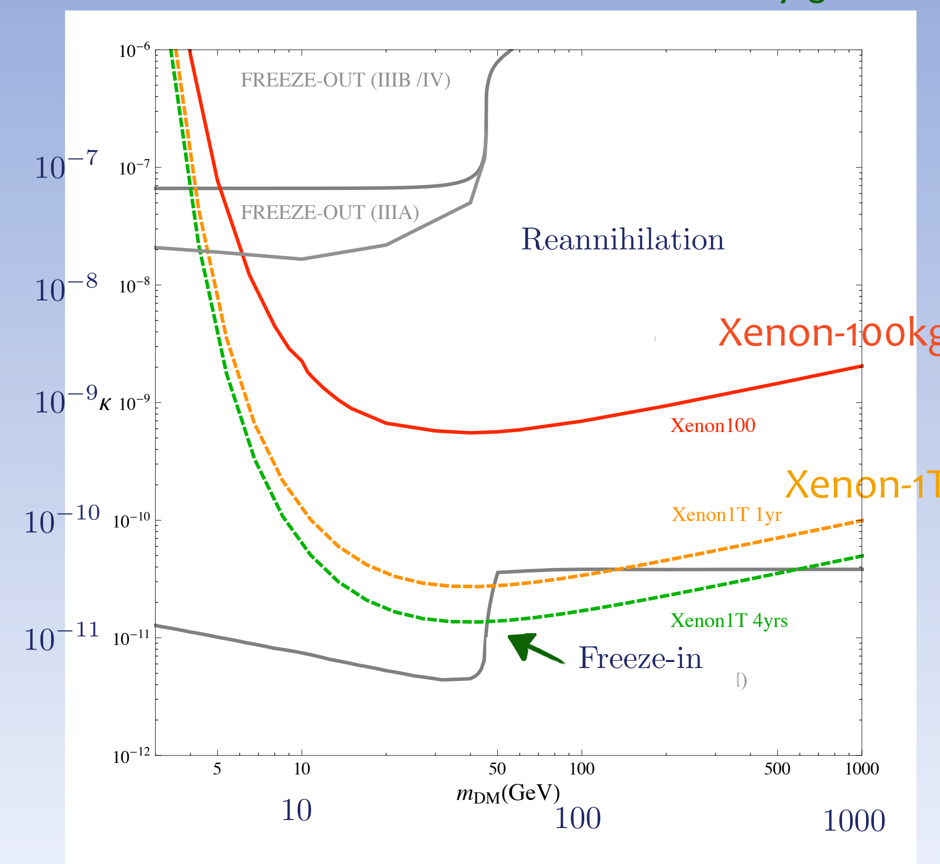
huge enhancement

direct detection sensitive to very small connector values

$$\frac{d\sigma}{dE_r} = \frac{1}{E_r^2} \frac{1}{v^2} \frac{2\pi\kappa^2 Z^2 \alpha^2}{m_A} F_A^2(qr_A)$$

$$\kappa = \epsilon \cdot \sqrt{\frac{\alpha'}{\alpha}}$$

Chu, T.H., Tytgat 11



m_{DM} (GeV)

.....,
Scwhetz, Zupan 11
Fornengo, Panci, Regis 11
Chu, T.H., Tytgat 11

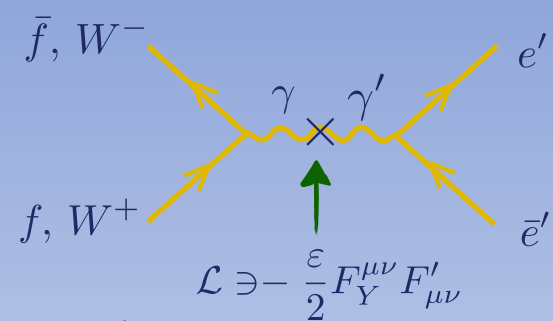
Visible sector/Hidden sector/Connector structure:

4 basic ways to get the observed relic density

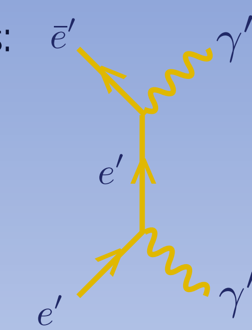
here for scenario with only visible sector at end of inflation

A DM fermion charged under a U(1) which kinetically mixes with the photon:

Connector processes:



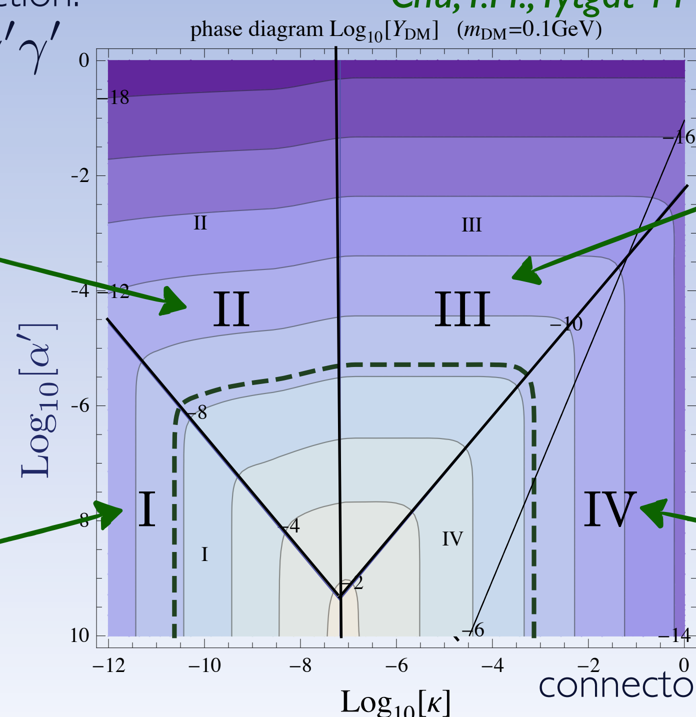
Hidden sector process:



hidden sector interaction:

$\bar{\psi}_{DM}\psi_{DM} \leftrightarrow \gamma'\gamma'$

Chu, T.H., Tytgat 11



Reannihilation regime

Hidden sector freeze-out regime

Freeze-in regime

Connector freeze-out regime

connector interaction:

$SM\, SM \leftrightarrow \bar{\psi}_{DM}\, \psi_{DM}$

See also Cheung, Ellor, Hall, Kumar 11 with slow decay

A simple Hidden Sector DM model example: Hidden vector DM

assume a non-abelian $SU(2)_X$ gauge structure fully spontaneously broken

by a $SU(2)_X$ scalar doublet ϕ

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

TH 07

"Hidden sector" — Hidden sector/SM connector

⇒ after $SU(2)_X$ sym. breaking:

$$\langle\phi\rangle = \begin{pmatrix} 0 \\ \frac{v_\phi}{\sqrt{2}} \end{pmatrix}$$

- 3 massive $SU(2)_X$ gauge bosons: stable: DM candidates
- one real scalar boson
- a remnant $SU(2)_C$ custodial symmetry

perfectly possible DM candidates in perturbative or confined phases

TH 07
TH, Tytgat 09
TH, Strumia 12

4 parameters: $g_X,\ \mu_\phi^2,\ \lambda_\phi,\ \lambda_m$

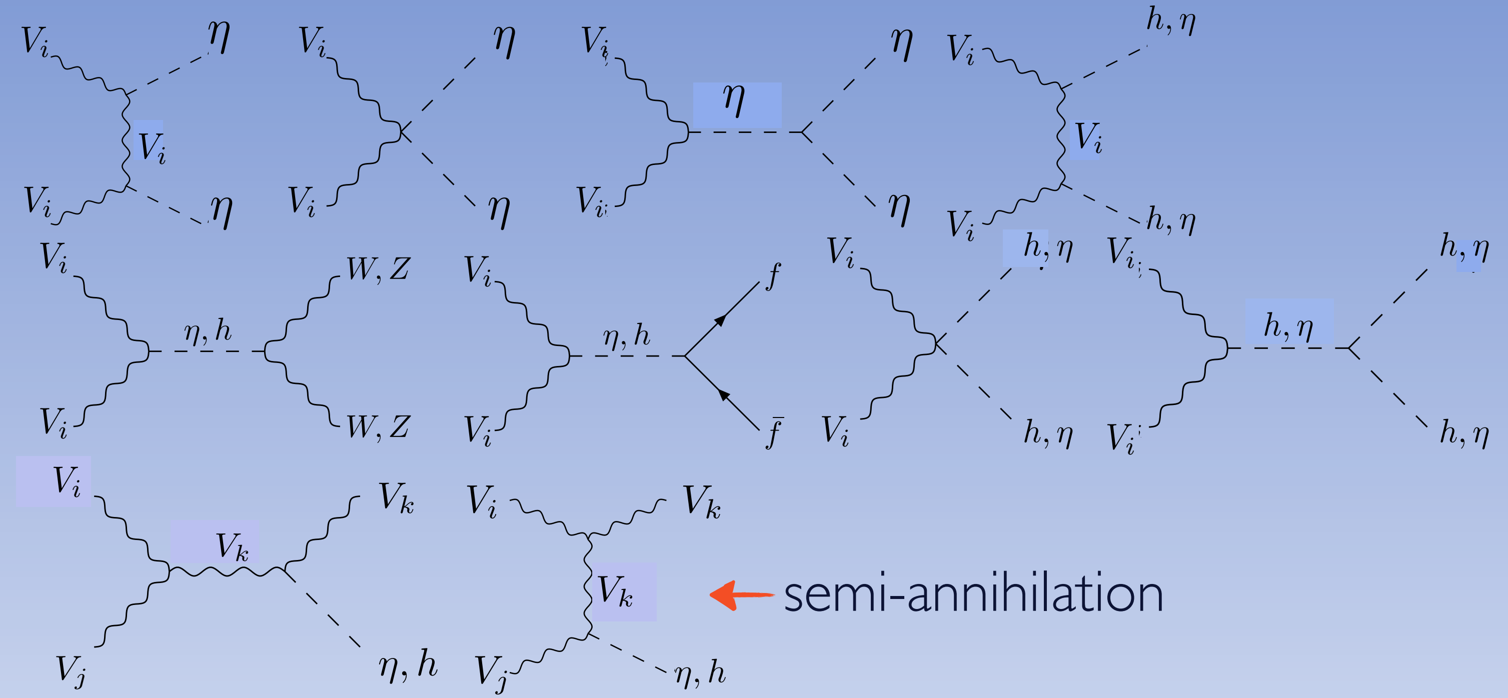
DM = hidden forces!

see also H. Davoudiasl, Lewis '13

Hidden vector DM

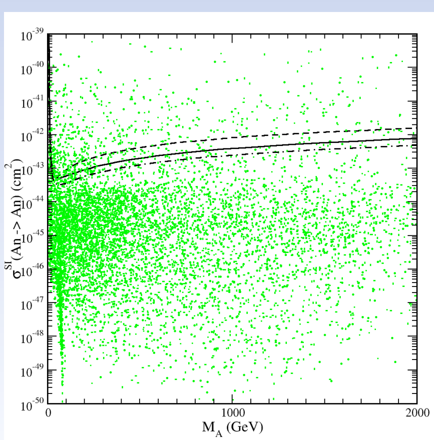
$SU(2)_X$ gauge bosons: perfectly viable DM candidates:

- relic density:



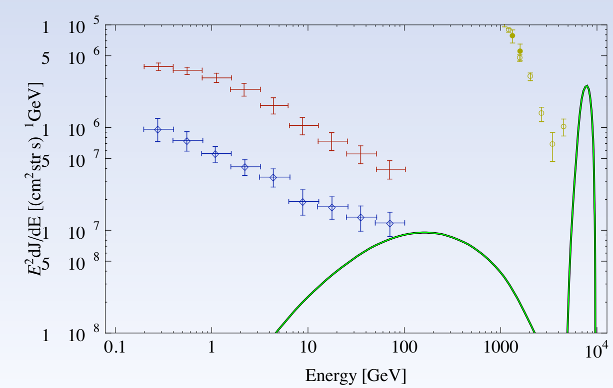
semi-annihilation

- direct detection: scalar exchange:



- indirect detection: γ-lines, ...

Arina, TH, Ibarra, Weniger 09



Brief conclusion

Establishing DM as a WIMP particle:

→ complementary phenomenological ways to test it from multichannel experiments

→ effective operators,
explicit mediators,
explicit models

→ direct detection,
indirect detection,
colliders

→ very promising experimentally for visible sector WIMP DM scenarios

→ clear possibilities for hidden sector DM models too (but easy to escape detection too)

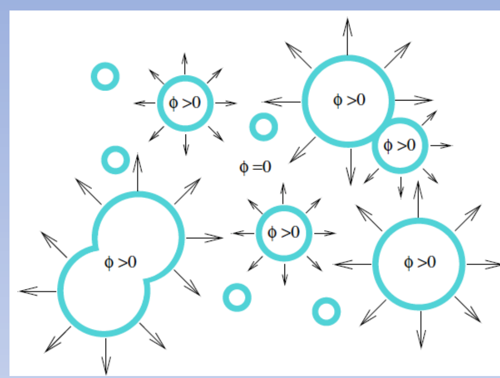
→ potentially related to many other BSM fundamental issues, at various possible levels

Is DM at TeV scale useful for anything else than DM??

relevant question whether or not: -one brings a solution for the hierarchy problem

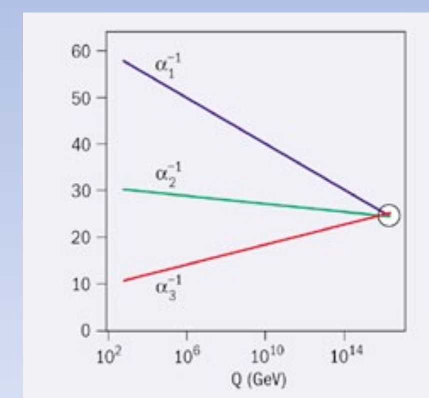
-one brings an explanation for $m_{DM} \sim \mathrm{TeV} \sim v_{EW}$

- DM at TeV scale could easily play a role for EW baryogenesis,



or even making it successful

- DM at TeV scale could constitute the unique ingredient missing for EW unification at GUT scale



for example $SO(10)$ setup with automatically stable fermion triplet DM

Frigerio, T.H. 10

"split SUSY without SUSY"

- DM at TeV scale could easily play a role for EWSB dynamics

DM particle stability issue

A WIMP do decay unless a symmetry forbids it ← unlike various non WIMP models (e.g. at lower scale)

↓ many models: an ad-hoc Z_2 sym.

more attractive reason??

- based on having DM as a large electroweak multiplet: accidental symmetry — *Cirelli, Fornengo, Strumia 06*
- based on a gauge symmetry: Z_2 remnant subgroup of broken GUT group
  - as R-parity in SUSY-GUT — *Mohapatra 86, Martin 92, Aulakh, Melfo, Rasin, Senjanovic 98*
  - as Z_2^{B-L} in non-susy SO(10) — *Kadastik, Kannike, Raidal 10, Frigerio, T.H. 10*
- based on a flavor symmetry — *Hirsch, Morisi, Peinado, Valle 10. Kajiyama, Kannike, Raidal 11, Lavoura, Morisi, Valle 12, Lopez-Honorez, Merlo 13, Kile 13*
- hidden sector DM: various simple possibilities:
  - -DM stable as electron
  - -DM stable as lightest neutrino
  - -DM stable as proton

  abelian or non-abelian accidental sym.

  T.H 07, T.H., Tytgat 09, Arina, T.H., Ibarra, Weniger 10

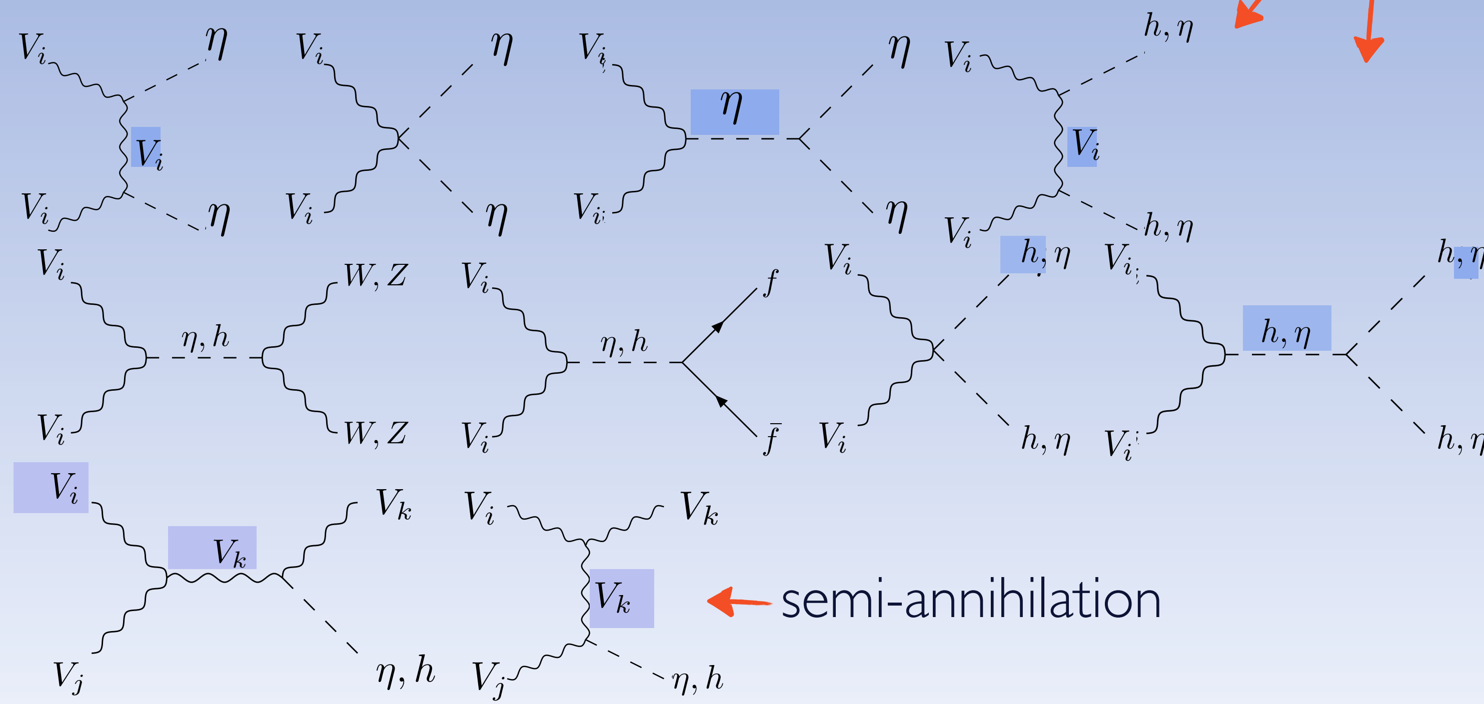
⇒ The stabilization mechanism determines many structural features of the all DM scenario

DM-EW scale issue

- I) A gauge coupling: could be reasonably expected of $\mathcal{O}(1)$ $\Rightarrow$ m_{DM} must be around TeV-few TeV

relic density constraint

gauge annihilations



DM-EW scale issue

- 2) If hidden vector at TeV scale $\Rightarrow$ it has easily an effect on EWSB

connector: $\mathcal{L} \ni -\lambda_m \phi^\dagger \phi H^\dagger H$

$$\ni -\frac{1}{2}\lambda_m v_\phi^2 \, H^\dagger H$$

a value $\langle \phi \rangle \sim m_{DM} \sim \mathrm{TeV}$ gives a contribution to m_h of order m_h^{exp} for $\lambda_m \sim 10^{-2,-3}$

$\Rightarrow$ a moderate connector gives a large effect on EWSB: $\leftarrow$ no surprise: an illustration of hierarchy problem, but here induced by the well motivated DM scale

if $\mu_H^2 < \mu_{H-SM}^2 \rightarrow \quad v_{EW} \sim m_{DM} \dfrac{1}{g_\phi} \sqrt{\dfrac{\lambda_m}{2\lambda_H}}$

Classically scale invariant case

T.H., Strumia '13

- 3) Starting from $\mu_H^2 = \mu_\phi^2 = 0$ ← no tree level HS gauge group sym. breaking, no tree level EWSB

→ Coleman Weinberg radiative (i.e. dynamical) sym. breaking of HS gauge group

→ $SU(2)_X$ DM gauge bosons loop induce a non trivial minimum for ϕ effective potential

→ induces EWSB through $\mathcal{L} \ni -\lambda_m \phi^\dagger \phi H^\dagger H$

↓

$$v_{EW} = v_\phi \sqrt{\frac{\lambda_m}{2\lambda_H}}$$

Visible sector Col.-W. vs Hidden sector Col.-W.

"inert scalar doublet"

- Visible sector: if DM is neutral component of scalar SM doublet H_2:

T.H., Tytgat '07

if $\mu_H^2 = \mu_{H_2}^2 = 0$: H_2 loops destabilize the H potential $\Rightarrow$ EWSB

$\hookrightarrow$ but requires large quartic scalar coupling

$\lambda_3 (H^\dagger H)(H_2^\dagger H_2)$
$\lambda_4 (H^\dagger H_2)(H_2^\dagger H)$
$\lambda_5 ((H^\dagger H_2)^2 + h.c.)$

$\leftarrow$ in order to compensate the large negative top loop contribution

$\Downarrow$

Landau pole(s) far below m_{Planck}

Hempfling '07

T.H., Strumia '13

- Hidden sector: no need for large scalar couplings: no Landau poles

Carone, Ramos '13; Khoze 13
Lindner, Schmidt, Watanabe 13
Salvio, Strumia 14
Khoze, Mc Cabe, Ro 14
C. Hill 14, Davoudiasl, Lewis '14
Alison, Hill, G.G. Ross 14
....

$\hookrightarrow$ $\mu_H^2 = \mu_\phi^2 = 0$ can be assumed at $\mu = m_{Planck}$

$\hookrightarrow$ $SU(2)_X$ sym. breaking when $\lambda_\phi < 0$ at $\mu << m_{Planck}$

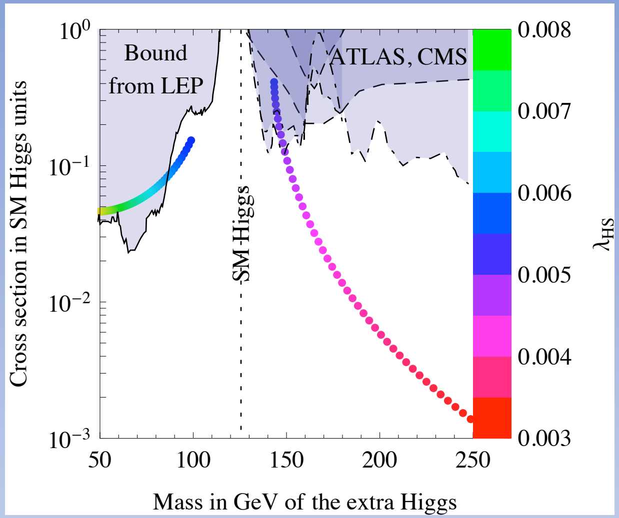
$\downarrow$

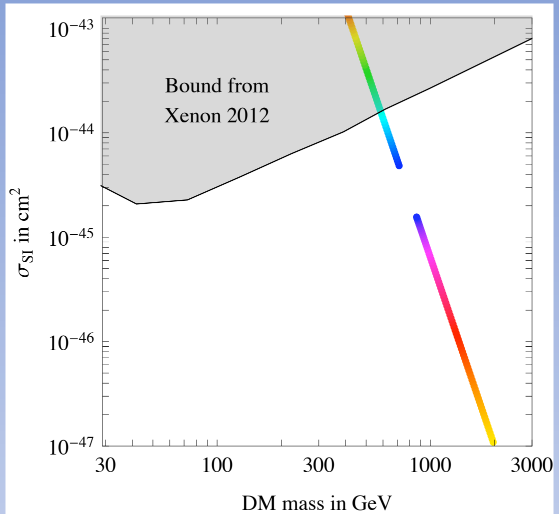
$V_{eff} \sim \beta_{\lambda_\phi} \phi^4 \ln s/s_*$ $\Rightarrow$ $v_{EW} \sim m_{DM} << m_{Planck}$

Phenomenology of scale invariant hidden vector setup

only 4 parameters: $g_\phi,\ \lambda_H,\ \lambda_\phi,\ \lambda_m$ $\Rightarrow$ once we fix $v_{EW},\ m_h,\ \Omega_{DM}$ only 1 param.: m_{DM}

production of the extra scalar at LHC





Direct Detection

T.H., Strumia '13

running up to m_{Planck}