Hunting BSM with DM: perspectives for a WIMP discovery

Thomas Hambye
Univ. of Brussels (ULB), Belgium

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No BSM at LHC (so far)

→ no sign of hierarchy problem motivated favorite BSM setups

⇒ one scenario: hierarchy problem remains the fundamental guiding principle

↓

SUSY for instance is at TeV scale rather than at 100 GeV

→ accepting some percent/per mil tuning (from 100 GeV to TeV)

→ but nothing in comparison with huge tuning
it still cures (from TeV to Planck scale)

↓

in this case SUSY still provides "natural" DM candidate

↓

for what concerns DM so far leaves
the neutralino option perfectly allright

No BSM at LHC (so far)

⇒ another scenario: hierarchy problem is not the right fundamental guiding principle (more plausible than before)

→ more difficult to see what kind of BSM could be there at TeV scale

→ but a series of BSM experimental facts remains

- neutrino masses
- baryogenesis
- dark matter ← good argument to expect DM below few TeV
- dark energy
- ...

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 $T \sim m_{DM}$

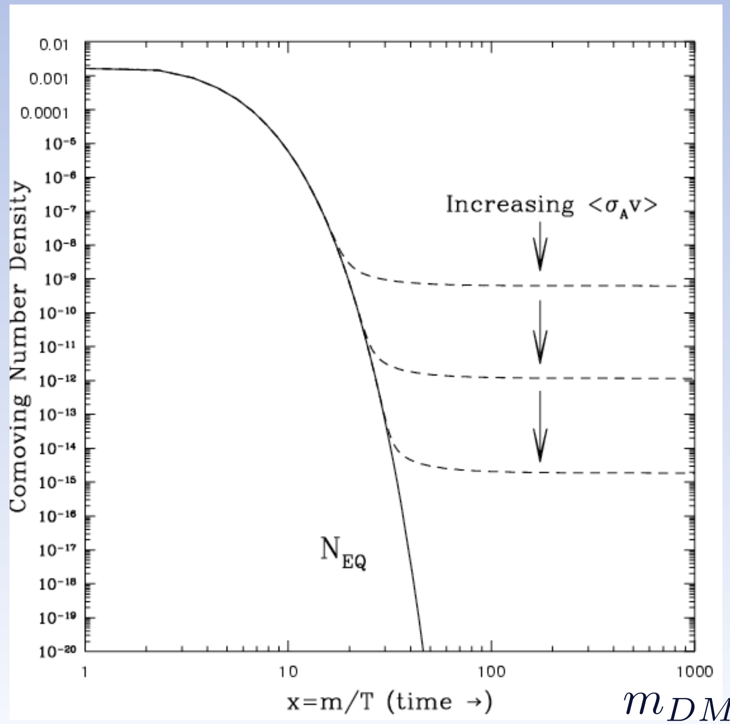
- SM-DM coupling not tiny ← $\lambda \gtrsim 10^{-7}$ for $m_{DM} \sim \text{TeV}$

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

→ 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

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

→ for electroweak couplings or couplings of order unity: $\Omega_{DM} \simeq 26\%$ requires $m_{DM} \sim \text{EW scale}$

$\langle \sigma_{annih.} v \rangle \simeq 10^{-26}\,\text{cm}^3/\text{sec}$

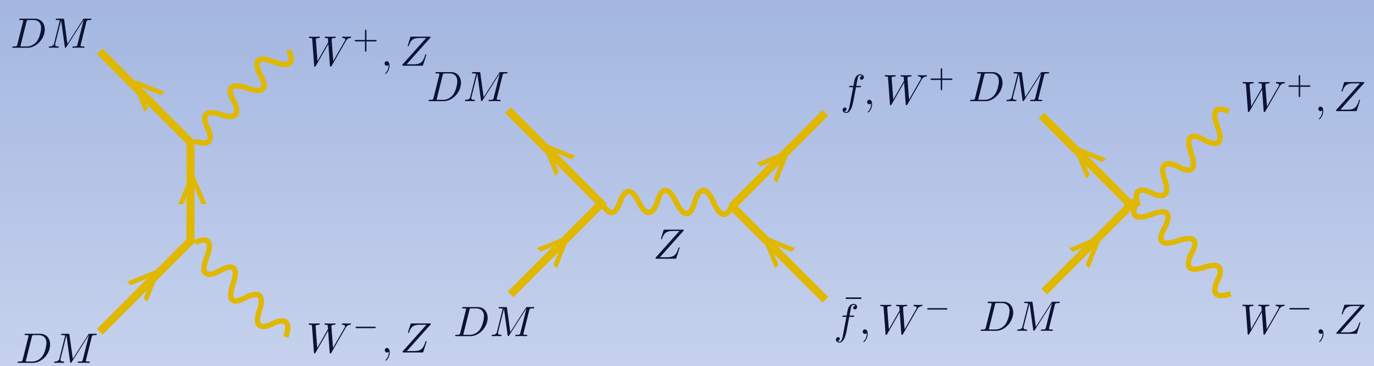
Most straightforward WIMP scale ~ TeV

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

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

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

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



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

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

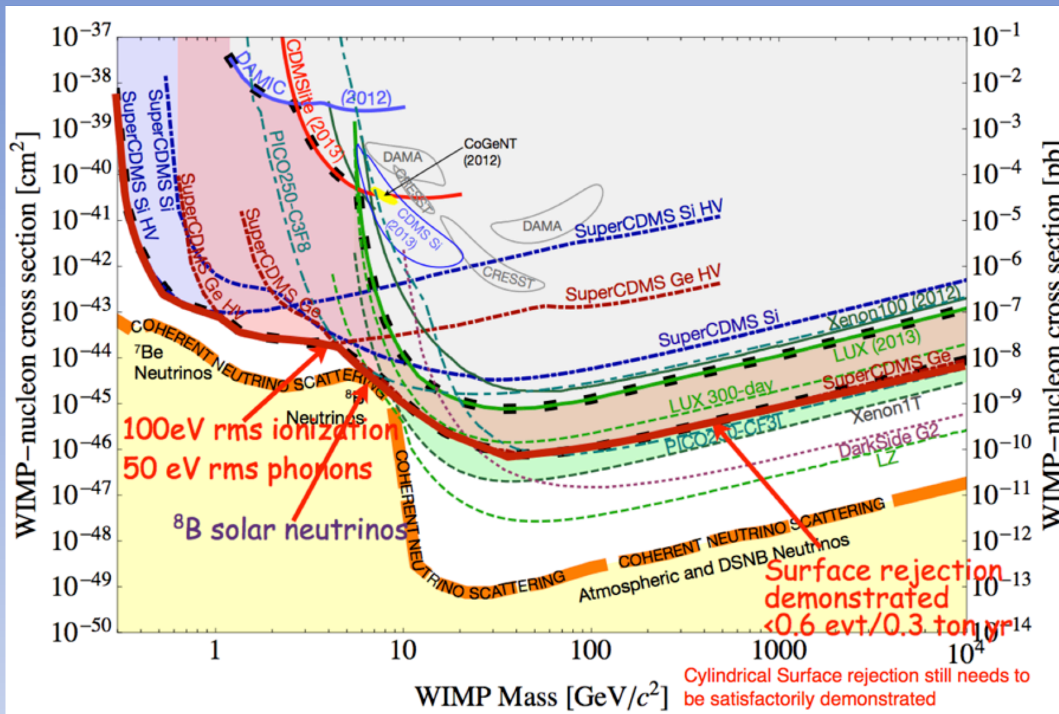
WIMP scale could also be lower or higher

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

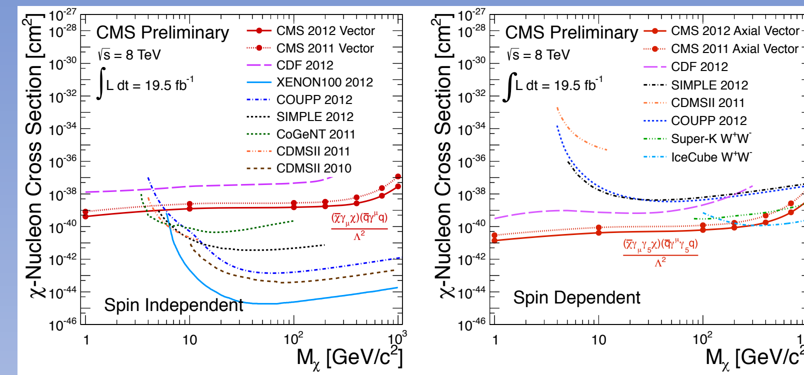
if Fermi suppression, or driven by smaller couplings, or interplay of channels, or small mass splittings, ...

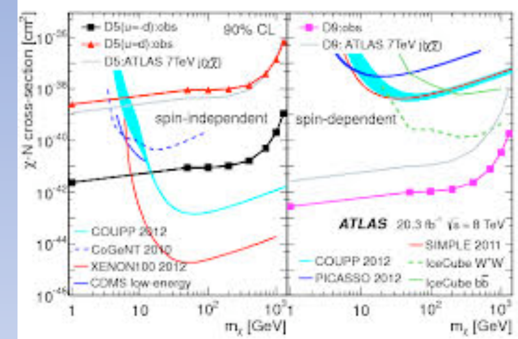
DM search: 3 main types of experiments

Direct detection: DM-N collision:



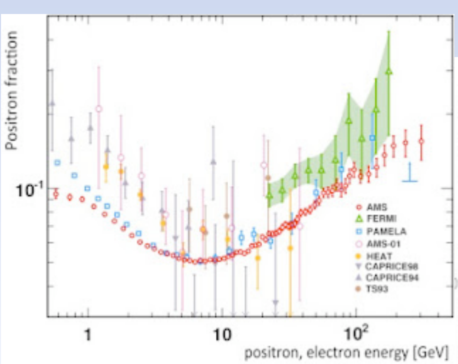
Colliders: DM pair production:

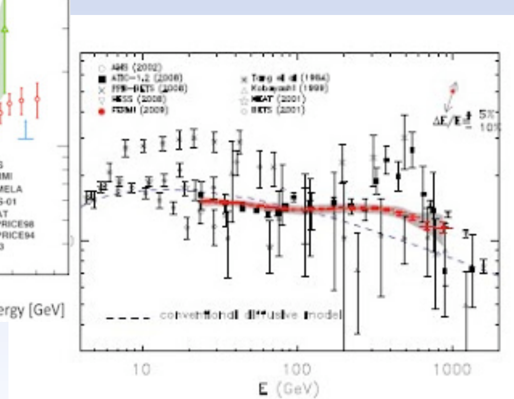


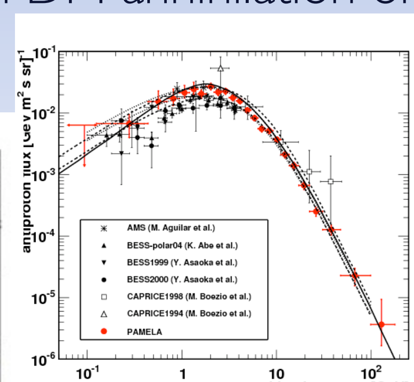


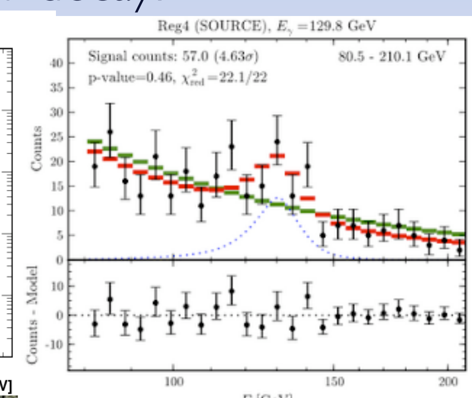
Monojets, monophoton, monoW/Z, cascade decays, ...

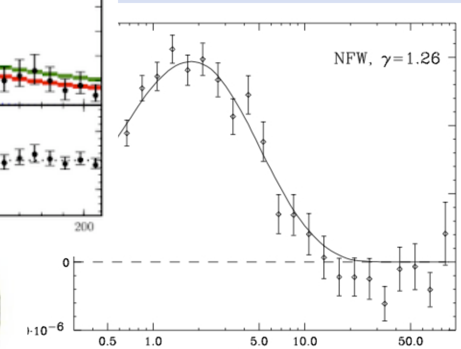
Indirect detection: cosmic rays from DM annihilation or decay:











3 main types of phenomenological approaches

Effective operators: most model independent approach

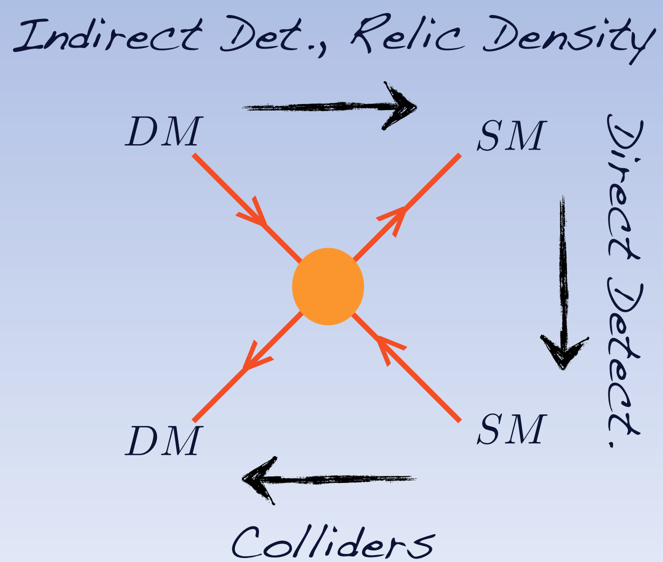
Explicit DM-SM mediator setups

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

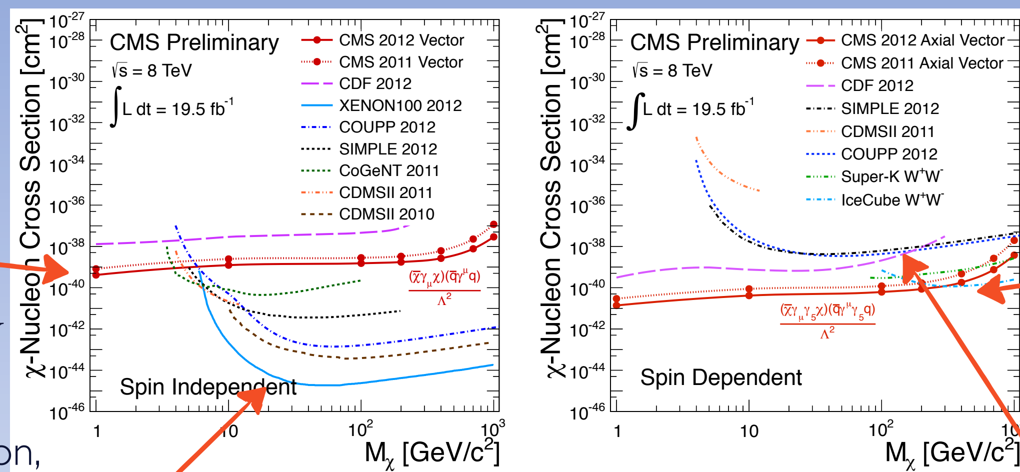
examples: vector and axial operators

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

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 $\sim 1\,\mathrm{TeV}$
from monojets, mono-photon, mono-W, ...

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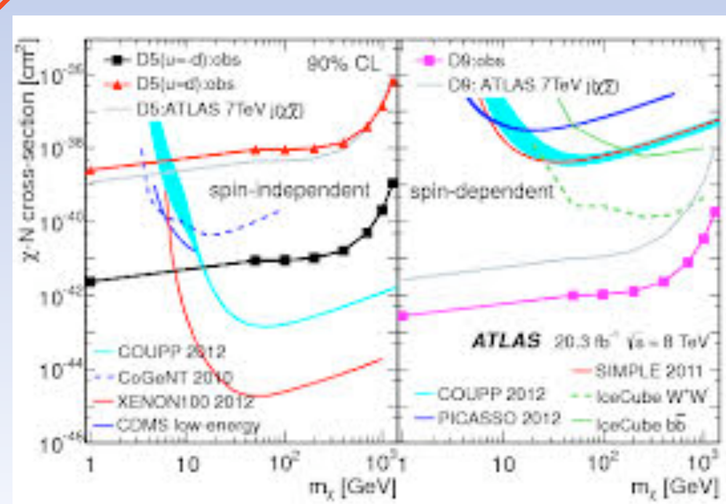


Direct Detect.:
$\Lambda \gtrsim 10\,\mathrm{TeV}$
for $10\,\mathrm{GeV} \gtrsim m_{DM} \gtrsim 1\,\mathrm{TeV}$

Direct Detect.:
$\Lambda \gtrsim 600\,\mathrm{GeV}$
for $10\,\mathrm{GeV} \gtrsim m_{DM} \gtrsim 1\,\mathrm{TeV}$

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

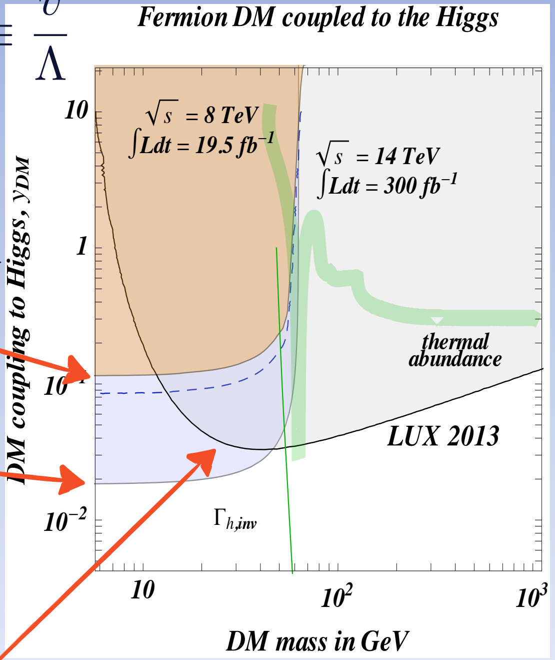
$$\mathcal{O} = \frac{1}{\Lambda} H^\dagger H \, \bar{\psi}_{DM} \psi_{DM}$$

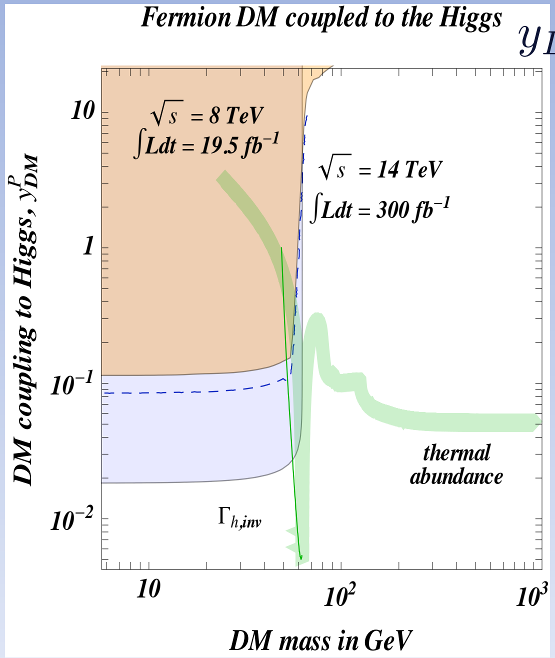
spin-independent direct detect.

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

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

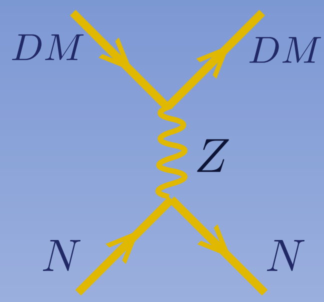
....

Direct Detect.: no relevant bound

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



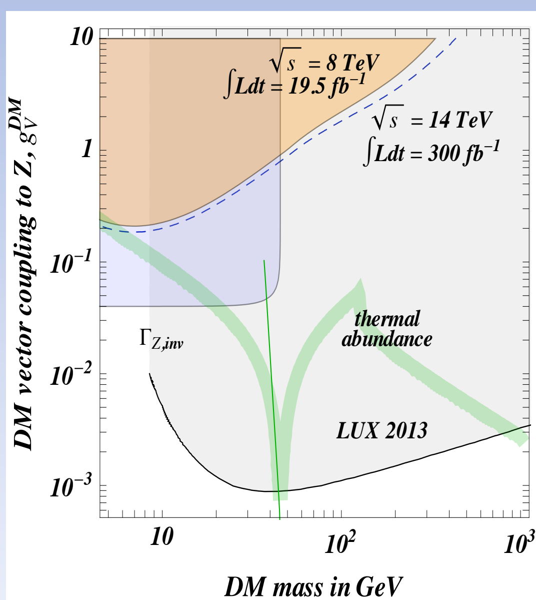
$$\mathcal{L} \ni -Z_\mu \frac{g}{\cos\theta_W} \bar{\psi}_{DM} (g_V^{DM} + g_A^{DM} \gamma_5) \gamma^\mu \psi_{DM}$$

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

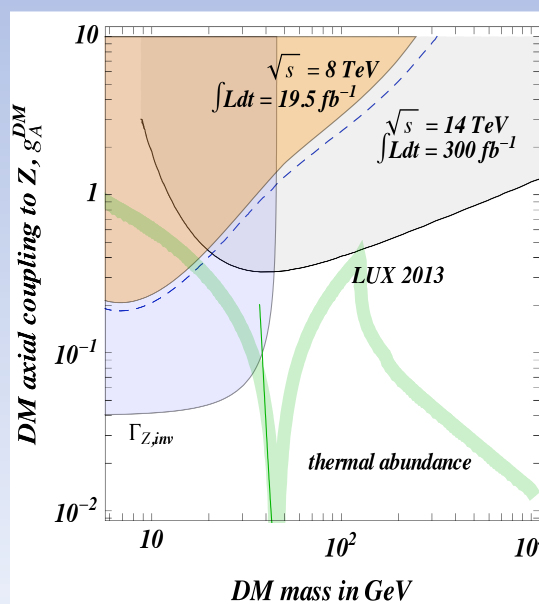
g_V^{DM}



↓

totally excluded for "standard" Z couplings

g_A^{DM}



↓

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

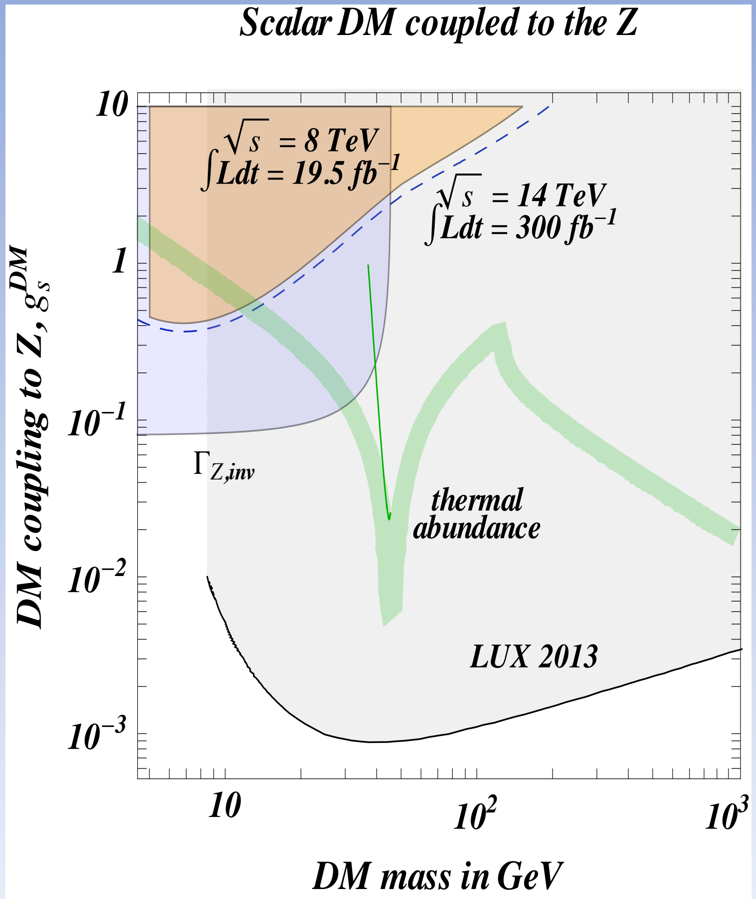
De Simone, Giudice, Strumia 14

....

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



De Simone, Giudice, Strumia 14

totally excluded for "standard" Z couplings

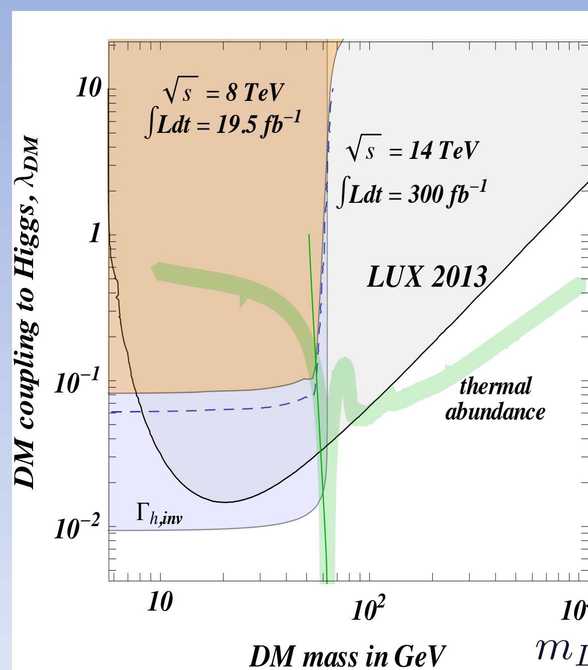
Explicit mediator approach: SM scalar mediator

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

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

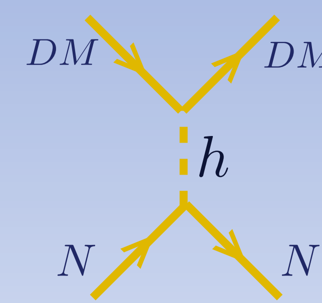
- Scalar DM: Higgs portal interaction: $\mathcal{L} \ni \lambda_{DM} H^\dagger H \; \phi^*_{DM} \phi_{DM}$

λ_{DM}



m_{DM} (GeV)

De Simone, Giudice, Strumia 14



⇓

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

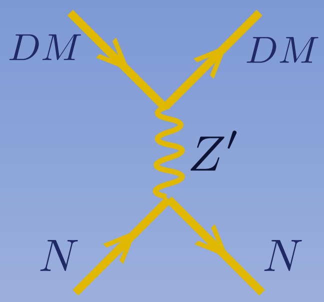
N.B.: Xenon1T will probe it up to $\sim 10\,\mathrm{TeV}$ for $\lambda_{DM} \sim 1$

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

Z' mediator

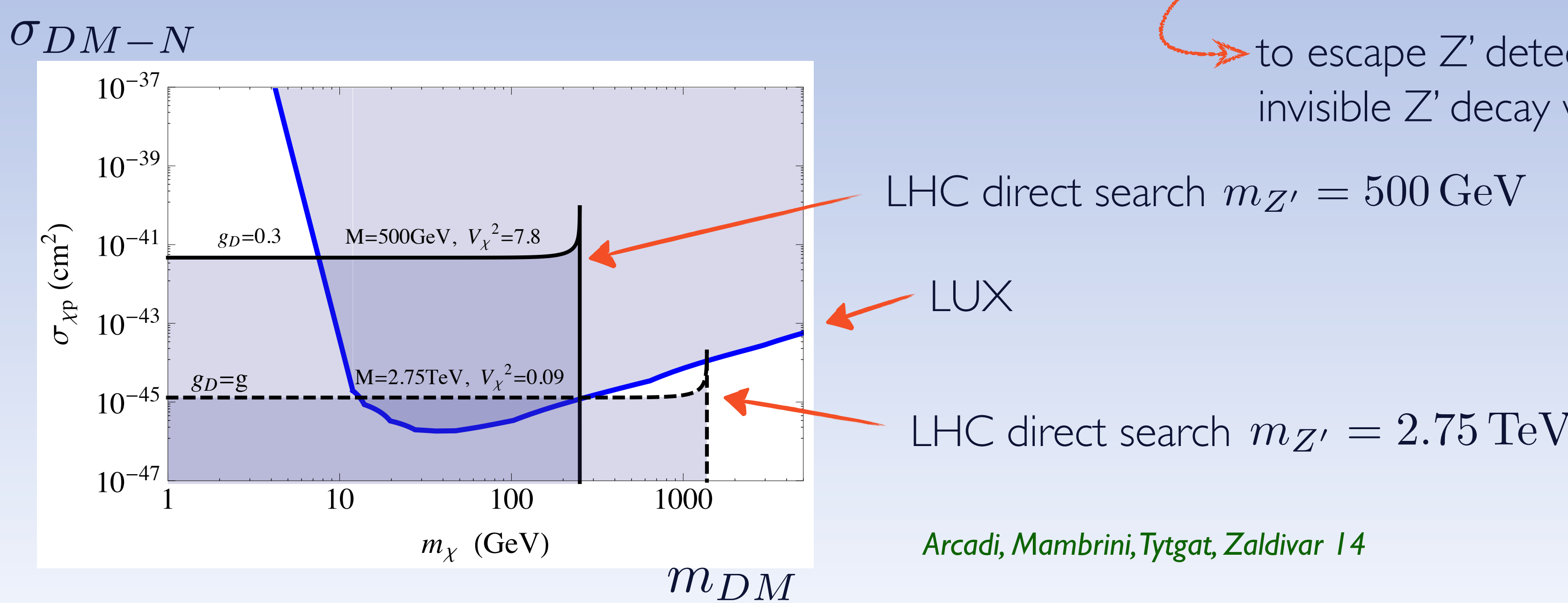
Similar phenomenology than for the Z exchange except that:

- bounds relax if Z' couplings to SM fields are smaller than for Z
- bounds relax for increasing values of $m_{Z'}$ and fixed m_{DM}



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

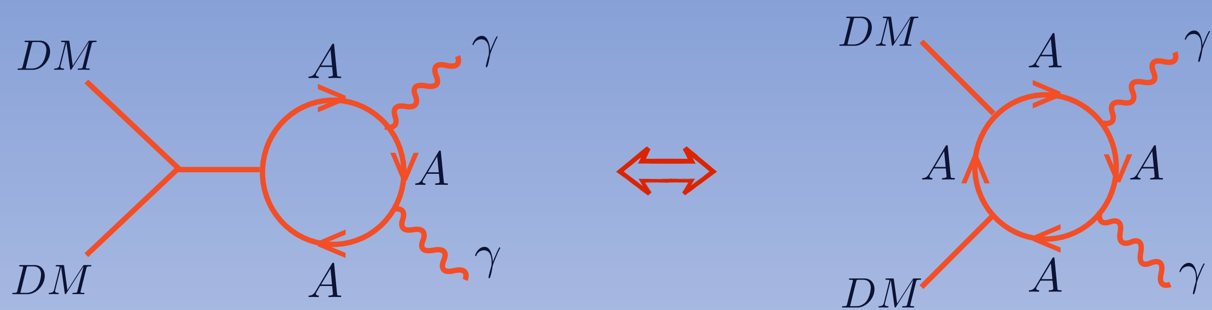


Arcadi, Mambrini, Tytgat, Zaldivar 14

Mediator for γ-lines and "gluon-lines"

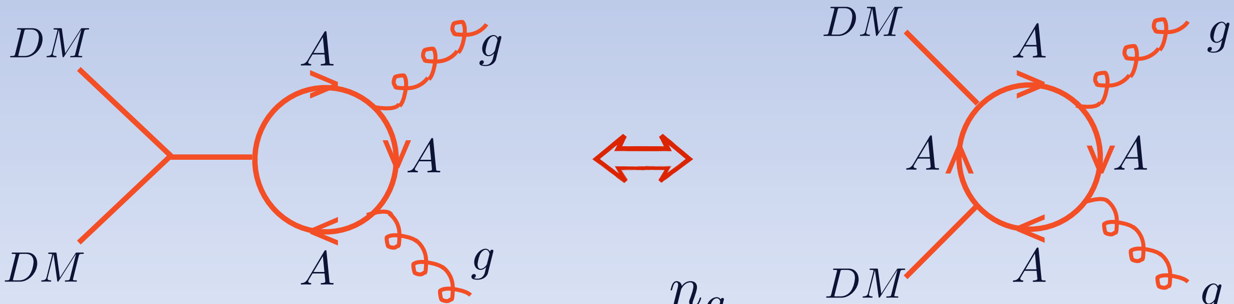
- γ-line emission production proceeds through photon emission from a charged particle in a loop

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



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

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



Chu, T.H., Scarna, Tytgat 12

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

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

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

⇒ many experimental consequences!

“Gluon lines” associated to γ-lines

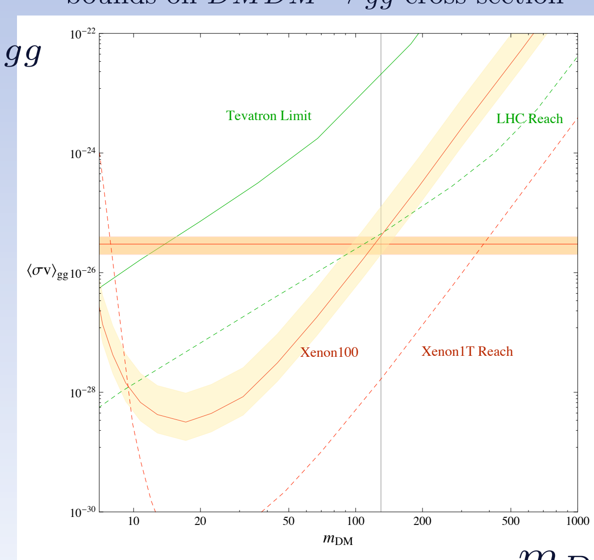
Many experimental consequences!

- 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

for a γ-line observed around current experimental sensitivity

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

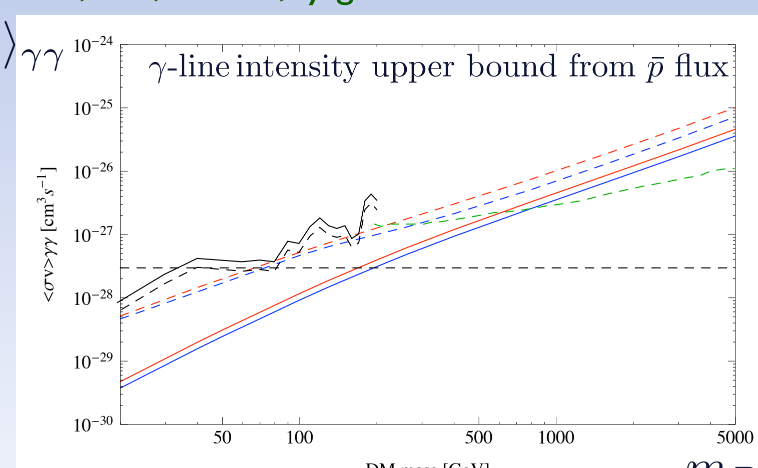
$\langle \sigma v \rangle_{gg}$



m_{DM}

Chu, T.H., Scarna, Tytgat 12

$\langle \sigma v \rangle_{\gamma\gamma}$



m_{DM}

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

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

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

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

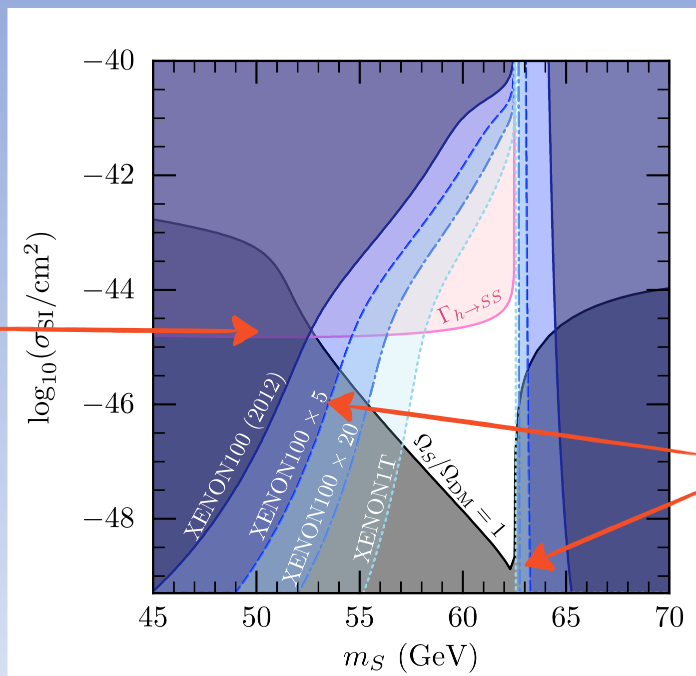
Explicit models: the simplest example: a real scalar singlet

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

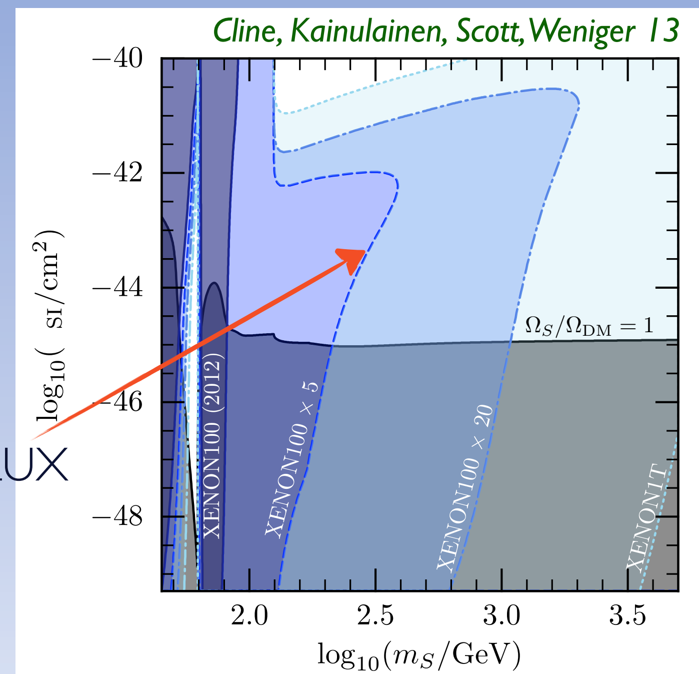
$$\mathcal{L} \ni -\frac{1}{2}\mu_S^2 S^2 - \frac{1}{24}\lambda_S S^4 - \frac{1}{2}\lambda_{hs} H^\dagger H S^2 \qquad m_S^2 = \mu_S^2 + \frac{1}{2}\lambda_{hs} v^2$$

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}

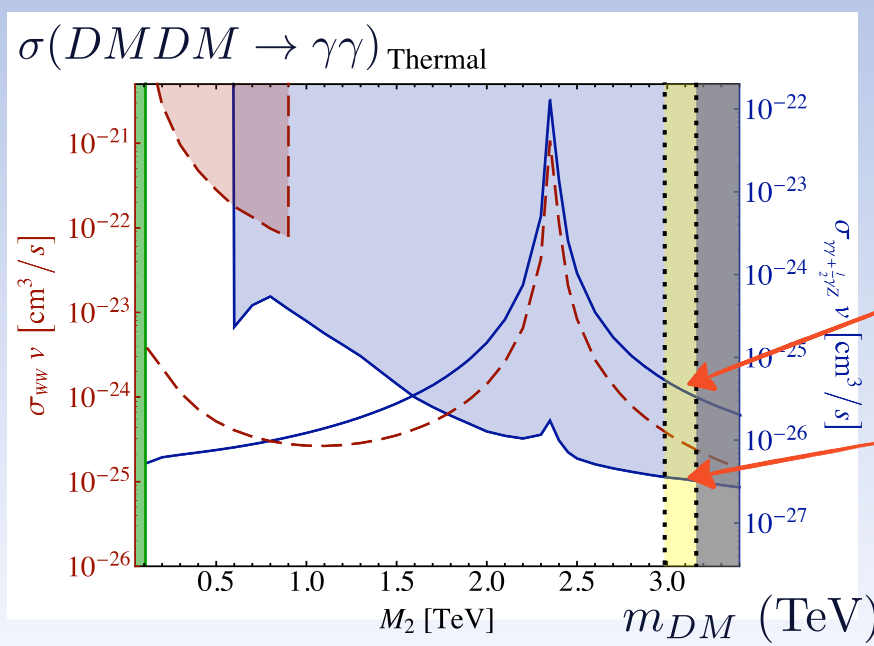
$\Omega_{DM} \simeq 26\%$ requires $m_{DM} \simeq 3.1\,\mathrm{TeV}$

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



Predicted flux (x4)

HESS upper limit

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

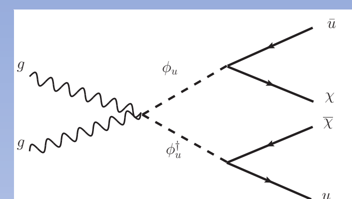
Explicit models: DM coupled to a colored partner

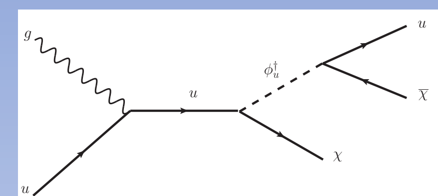
many proposals to couple DM directly to a colored partner

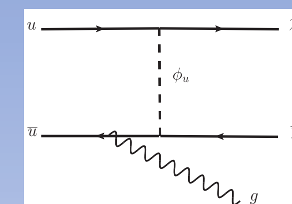
- Example: $\mathcal{L} \ni \lambda_u \, \bar{\chi}_{DM} \, u_R \, \phi_c$ — *Bai, Berger 13*

  scalar colored triplet

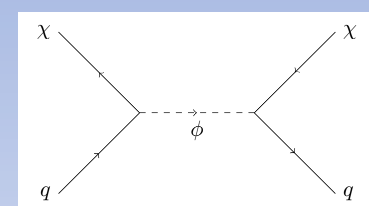
many ways to produce DM at colliders in unsuppressed way

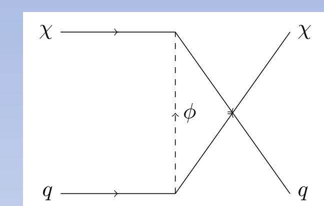






unsuppressed direct detection in s channel

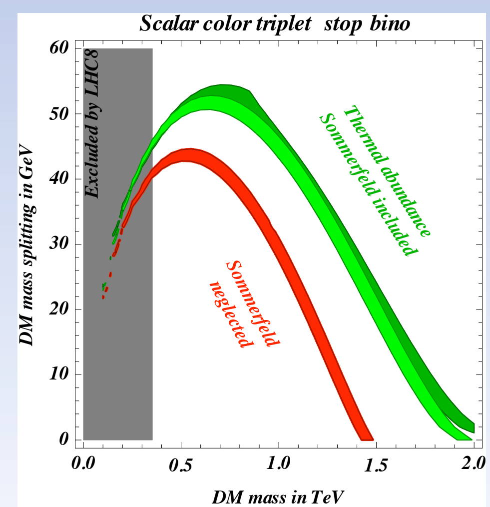




- DM coannihilation with a color partner

  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

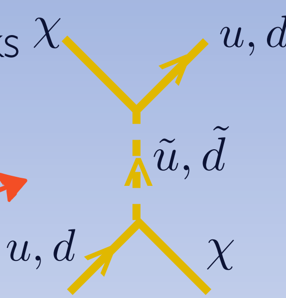
- Main impact of the LHC on MSSM: colored sector: $m_{\tilde{g}} \gtrsim 1\,\mathrm{TeV}$

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

  ⤷ 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 must be Bino dominated

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

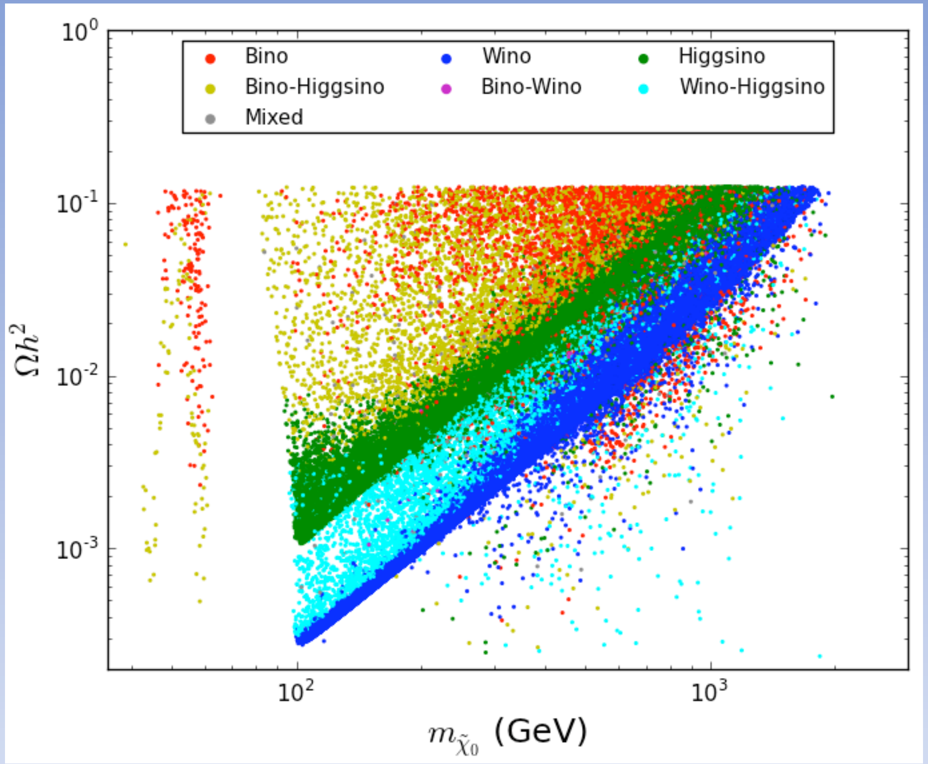
  if $m_\chi \gtrsim 500\,\mathrm{GeV}$ neutralino can be easily Higgsino dominated

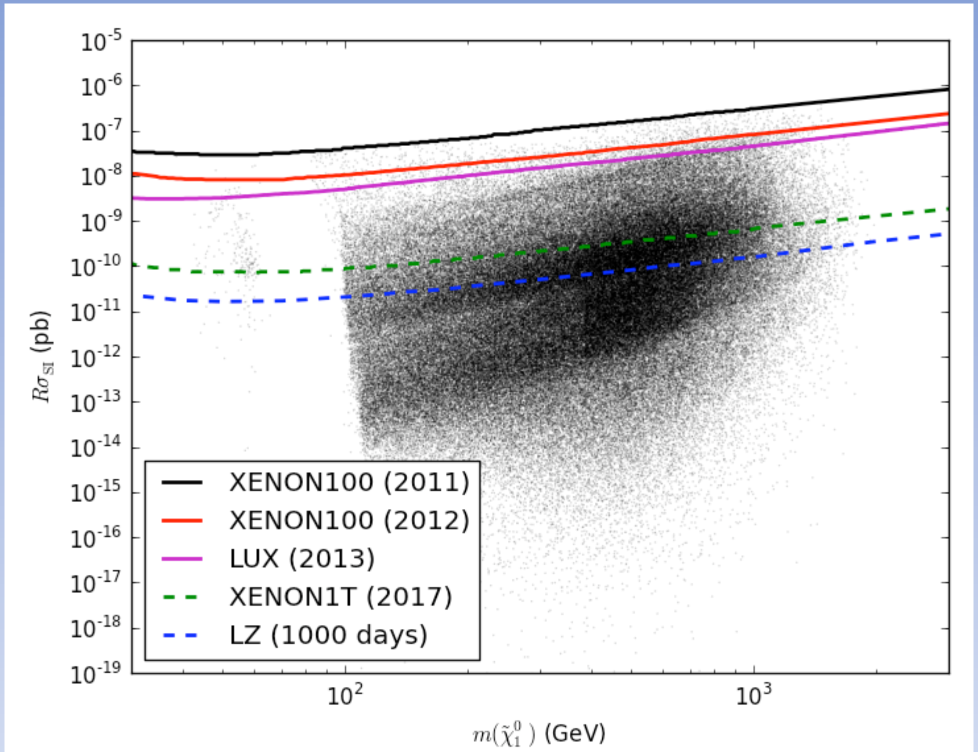
  if neutralino is Wino dominated its mass must be $m_\chi \sim 3\,\mathrm{TeV}$

Explicit models: MSSM neutralino

$pMSSM$ (19 parameters)

Rizzo 14, ...





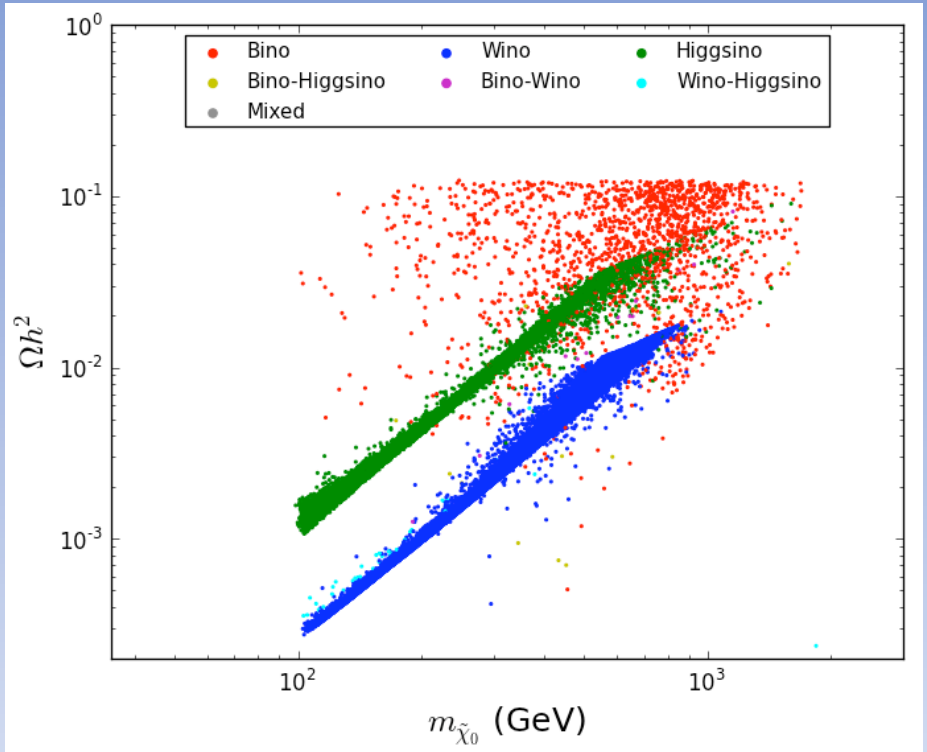
relic density point out a neutralino below ~3 TeV (i.e. gauge driven, or loop driven, ...) but could be higher

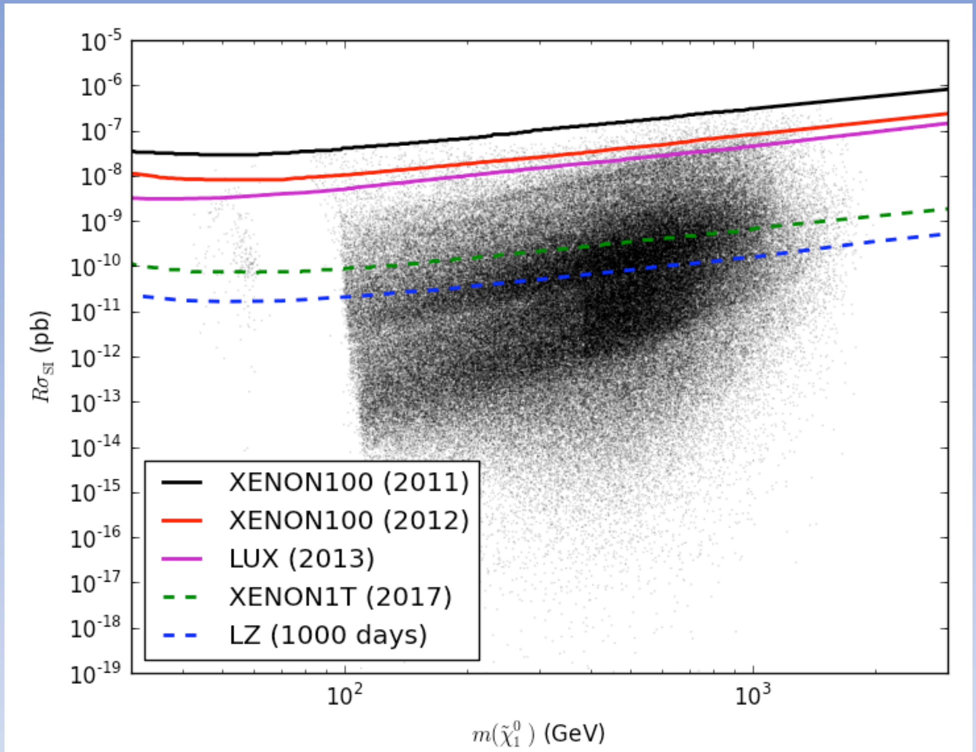
still not much probed by direct detection but Xenon1T, LZ, ..., will probe it substantially

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*
....

VISIBLE SECTOR ⟷ HIDDEN SECTOR

connector

VISIBLE SECTOR: with its own gauge groups

HIDDEN SECTOR: with its own gauge groups ← including DM stabilization mechanism and DM annihilation

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, ...

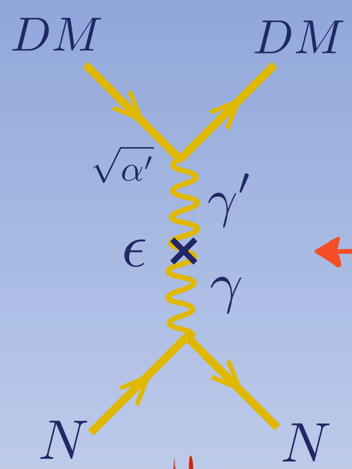
Berezhiani, Comelli, Villante 01
Feng, Tu, Yu 08
Ackerman, Buckley, Carroll, Kamionkowski, 09
Feng, Kaplinghat, Tu, Yu 09
Berezhiani, Lepidi 09
Mc Dermott, Yu, Zurek 10 , ...

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

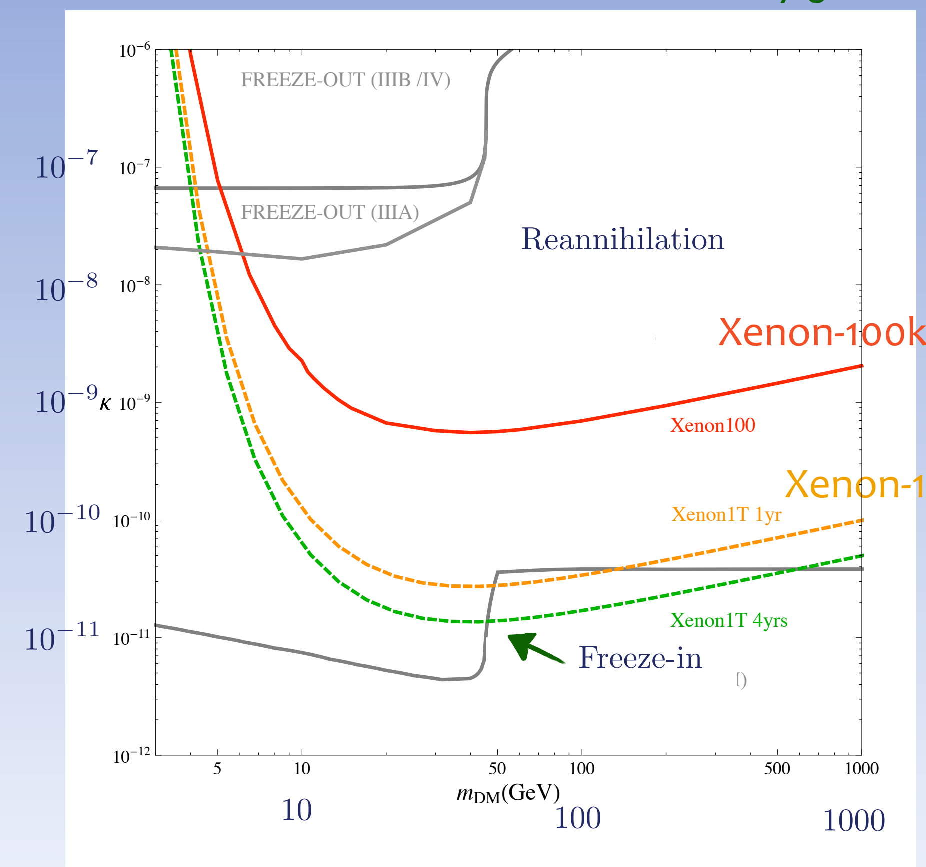
huge enhancement

direct detection sensitive to very small connector values

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

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

Chu, T.H., Tytgat 11



m_{DM} (GeV)

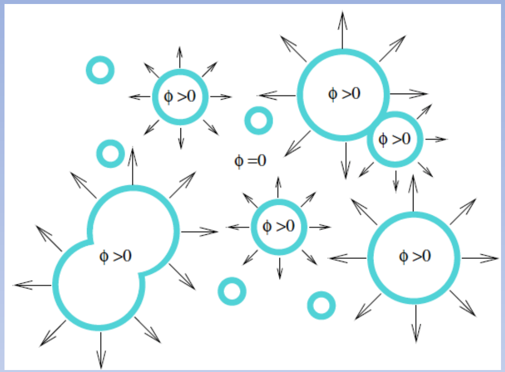
.....,
Scwhetz, Zupan 11
Fornengo, Panci, Regis 11
Chu, T.H., Tytgat 11

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

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

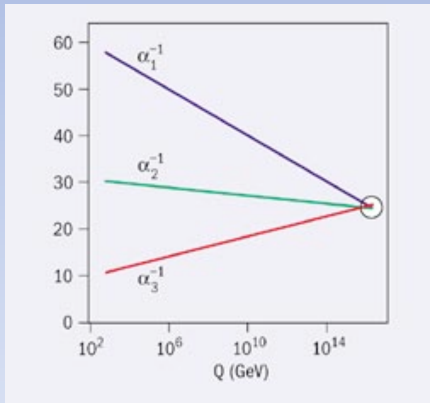
-one brings an explanation for $m_{DM} \sim \mathrm{TeV} \sim v_{EW}$

- 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-EW scale coincidence: impact of DM on EWSB

WIMP generic scale is right where it could play a role for EWSB

→ recent revival of the old Coleman-Weinberg radiative sym. breaking mechanism:

DM being at TeV scale could drive EWSB: $v_{EW} \sim m_{DM} \sim TeV$

→ not a solution to hierarchy problem: assumes $\mu^2 \simeq 0$ at Planck scale

if this conjecture is done it gives $m_{DM} << m_{Planck}$

$v_{EW} \sim m_{DM} \sim TeV$

→ with inert doublet scalar DM *T.H., Tytgat 07*

→ with hidden vector DM *T.H., Strumia 13*

Carone, Ramos 13
Khoze 13
Lindner, Schmidt, Watanabe 13
Salvio, Strumia 14
Khoze, Mc Cabe, Ro 14,
....

Brief conclusion

Establishing DM as a particle:

↪ complementary phenomenological ways to test it from multichannel experiments

↪ very promising experimentally for the WIMP scenario for visible sector DM models

↪ 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

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, ...

- 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:

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

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

for a fermion DM candidate:

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

$$O^{1Y}_{DM} \equiv \bar{\ } \ _{\mu} \ \ _{DM} F^{\mu}_{Y} \qquad \bar{\ } \cdot \ _{DM} \cdot \ = (1,0)$$
$$O^{1L}_{DM} \equiv \bar{\ } \ _{\mu} \ \ _{DM} F^{\mu}_{L} \qquad \bar{\ } \cdot \ _{DM} \cdot \ = (3,0)$$
$$O^{2Y}_{DM} \equiv D_{\mu} \bar{\ } \ \ _{DM} F^{\mu}_{Y} \qquad \bar{\ } \cdot \ _{DM} = (1,0)$$
$$O^{2L}_{DM} \equiv D_{\mu} \bar{\ } \ \ _{DM} F^{\mu}_{L} \qquad \bar{\ } \cdot \ _{DM} = (3,0)$$
$$O^{3Y}_{DM} \equiv \bar{\ } \ _{\mu} D \ \ _{DM} F^{\mu}_{Y} \qquad \bar{\ } \cdot \ _{DM} = (1,0)$$
$$O^{3L}_{DM} \equiv \bar{\ } \ _{\mu} D \ \ _{DM} F^{\mu}_{L} \qquad \bar{\ } \cdot \ _{DM} = (3,0)$$

for a spin-1 DM candidate:

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

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

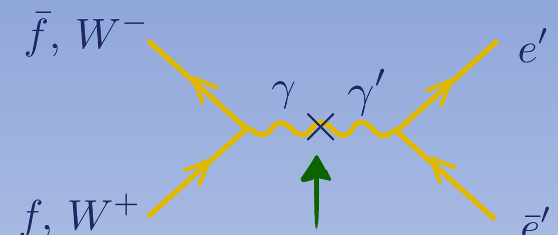
Visible sector/Hidden sector/Connector structure:

4 basic ways to get the observed relic density

here for scenario with only visible sector at end of inflation

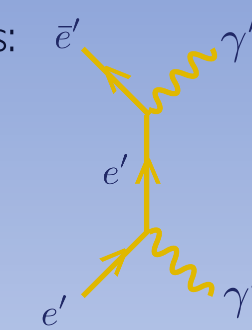
A DM fermion charged under a U(1) which kinetically mixes with the photon:

Connector processes:



$$\mathcal{L} \ni -\frac{\varepsilon}{2} F_Y^{\mu\nu} F'_{\mu\nu}$$

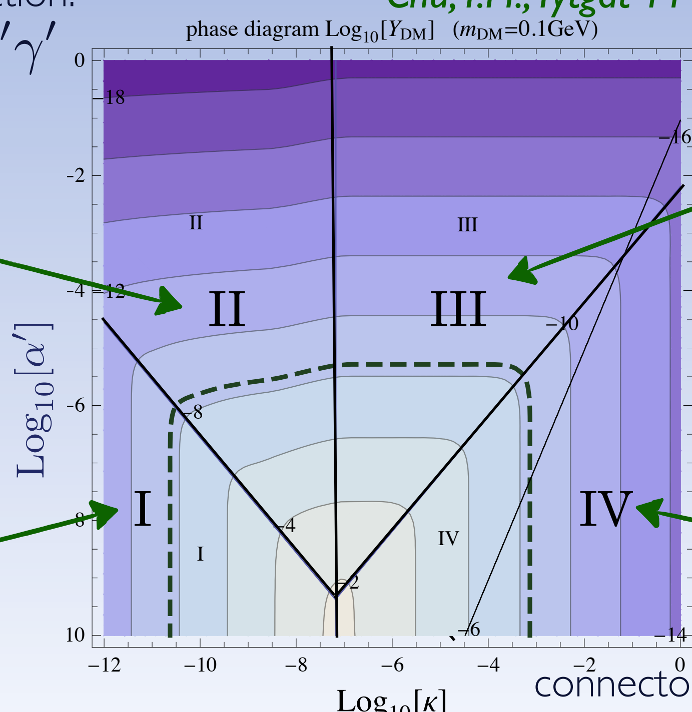
Hidden sector process:



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

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

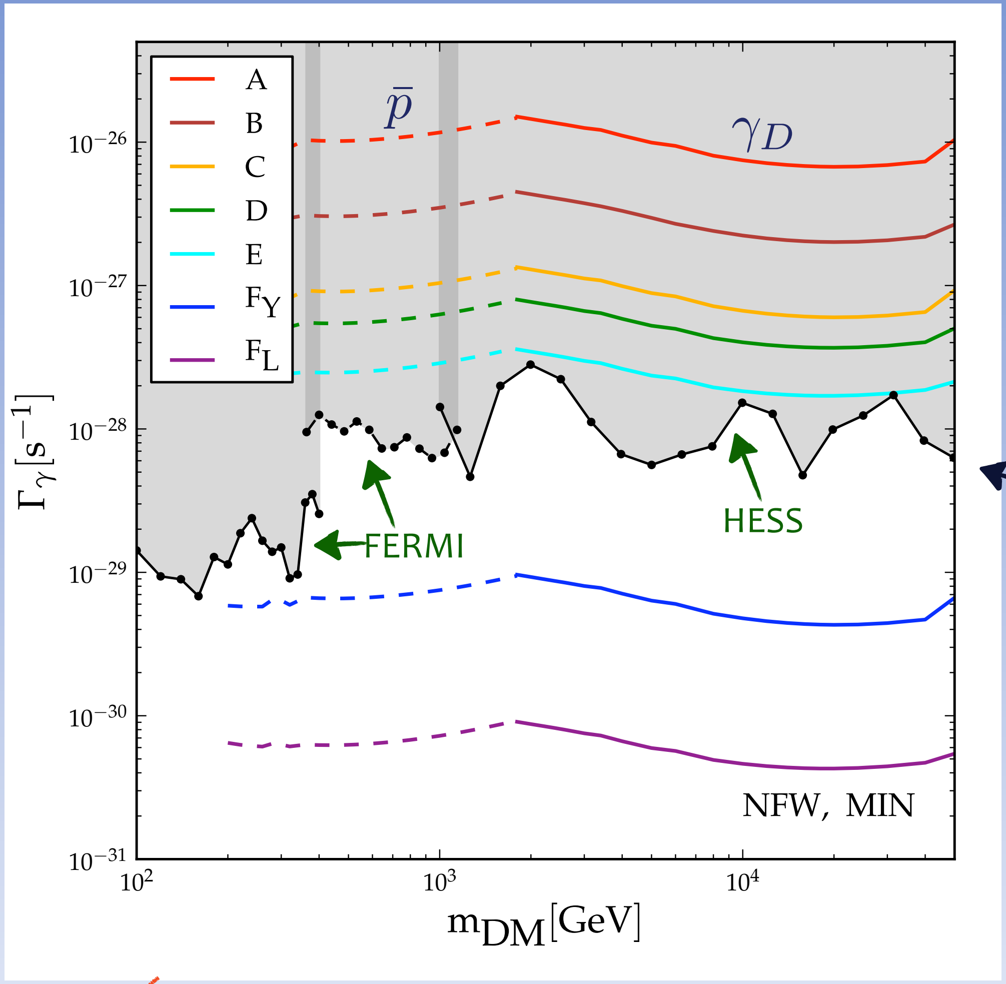
  abelian or non-abelian accidental sym.

  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

Upper bounds on γ-line intensity from DMdecay

Gustafsson, T.H., Scarna 13



upper bounds depending 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