WIMP Theory

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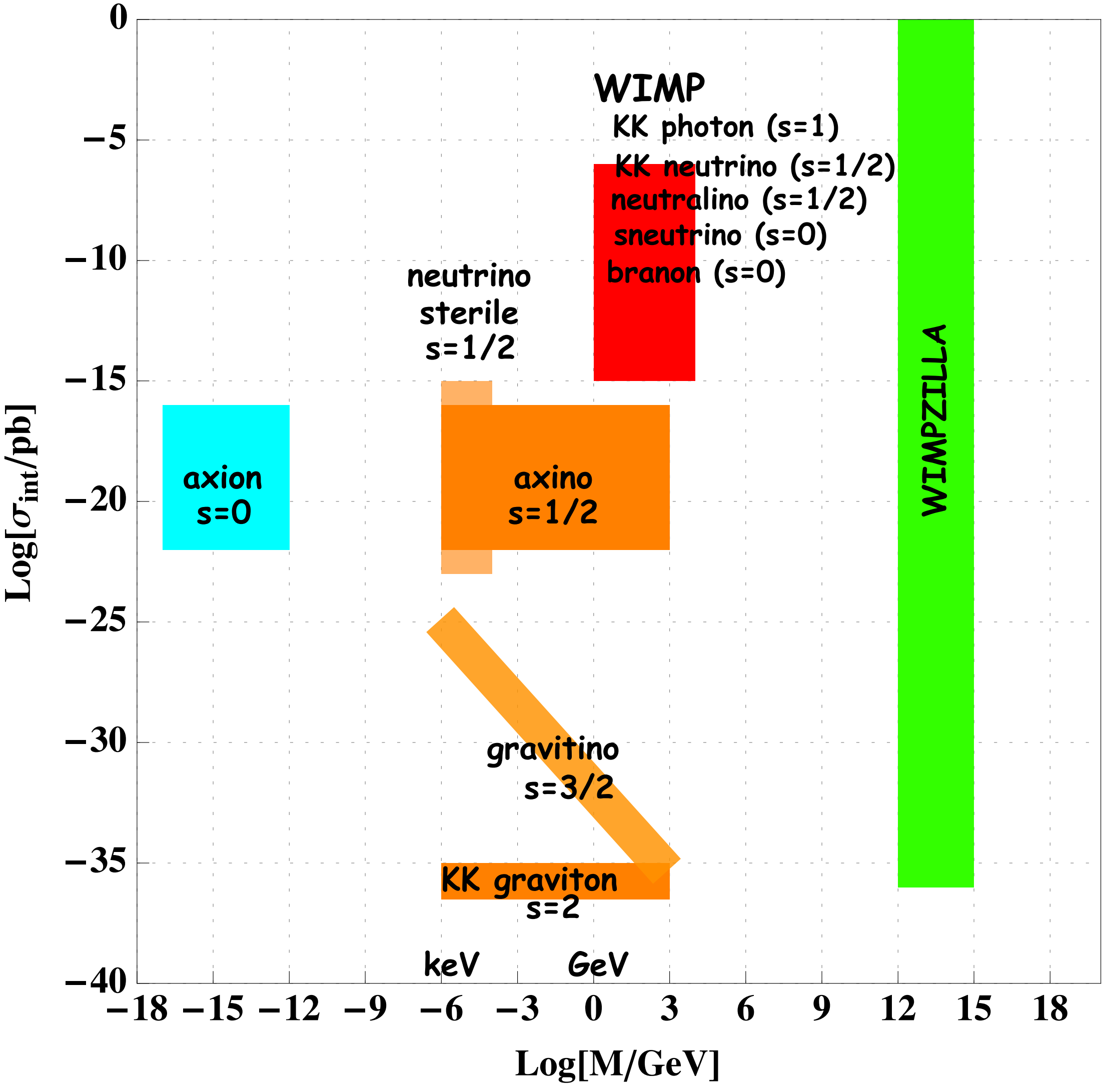
Dark Matter Candidates

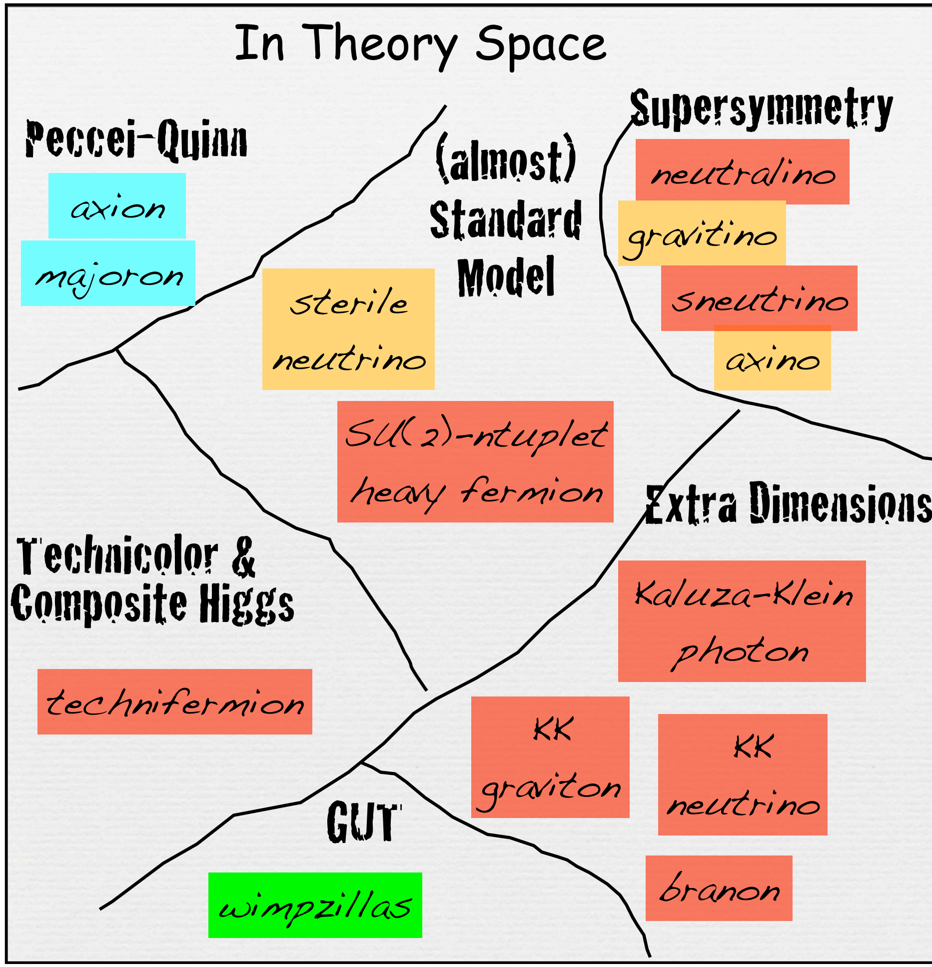


🟥 thermal relic

🟧 superWIMP

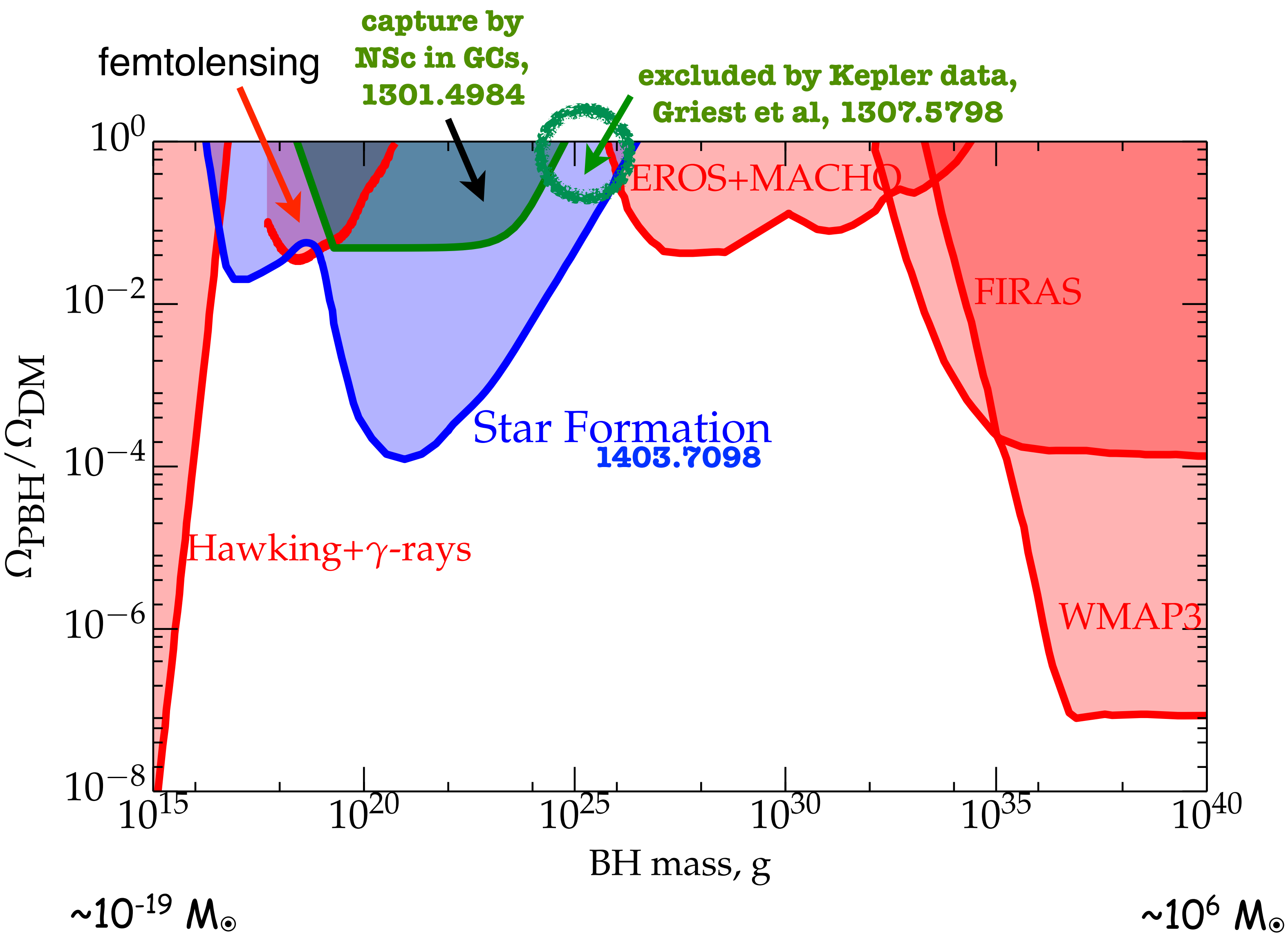
🟦 condensate

🟩 gravitationnally produced or at preheating



Constraints on Primordial Black Holes (PBHs) as Dark Matter

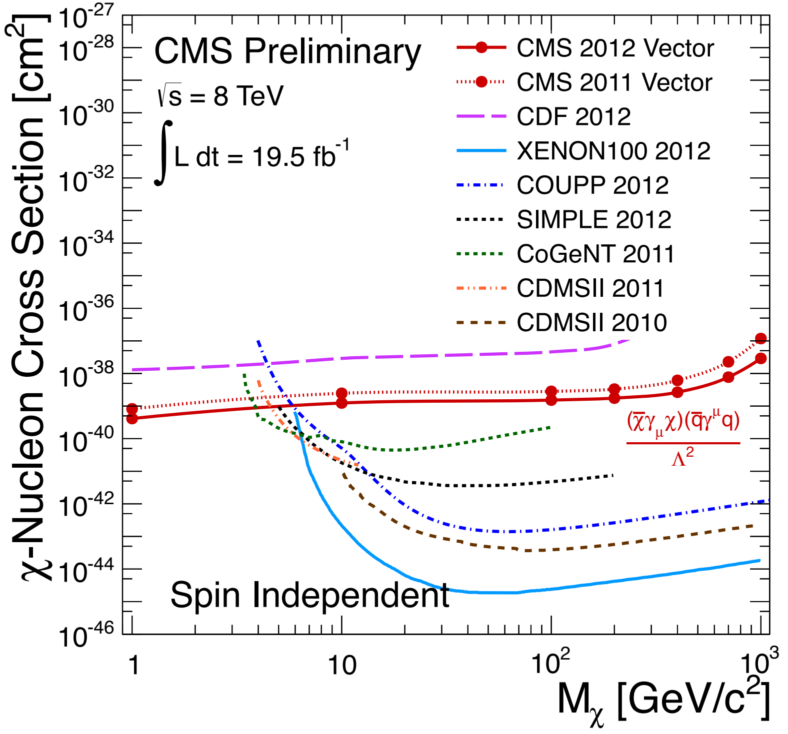
Tinyakov et al.

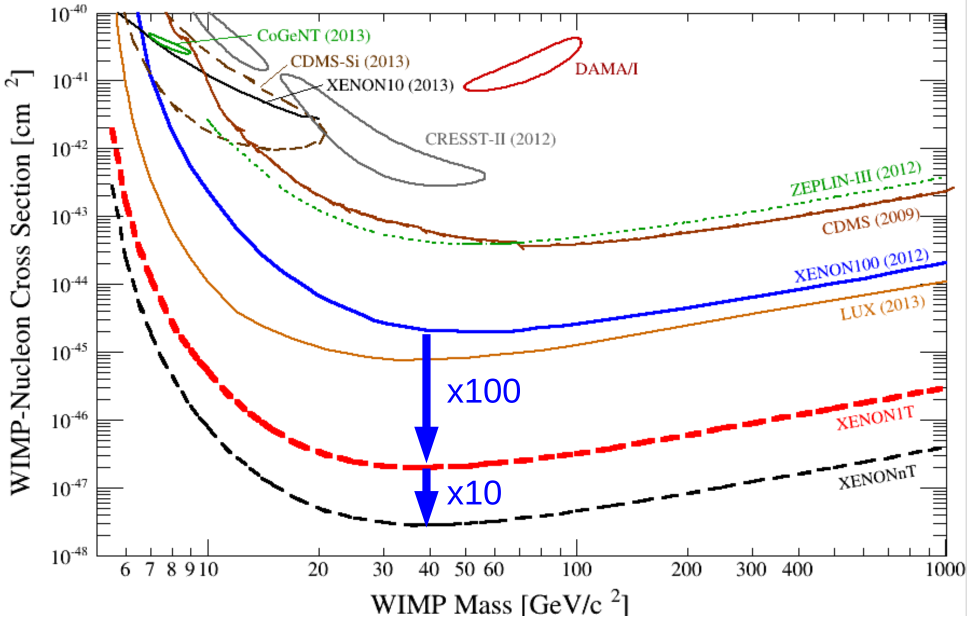


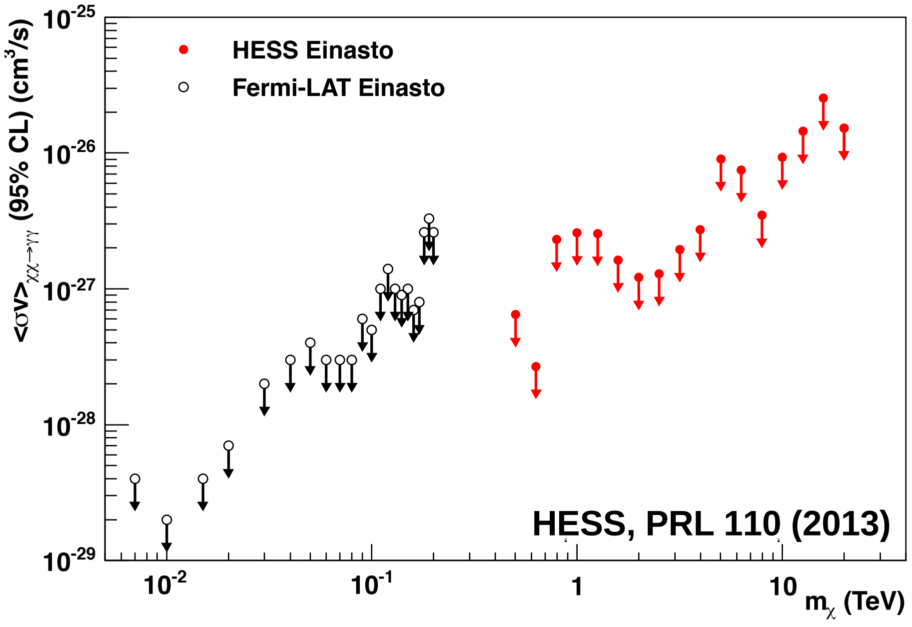
(biased) selection of topics discussed in this talk:

- Higgs-portal models
- MSSM
- KK DM in minimal UED
- Weight-philic DM
- Higgsogenesis
- Asymmetric DM (their indirect signals)

Wimps under pressure
from the LHC, Fermi, Xenon, LUX ...





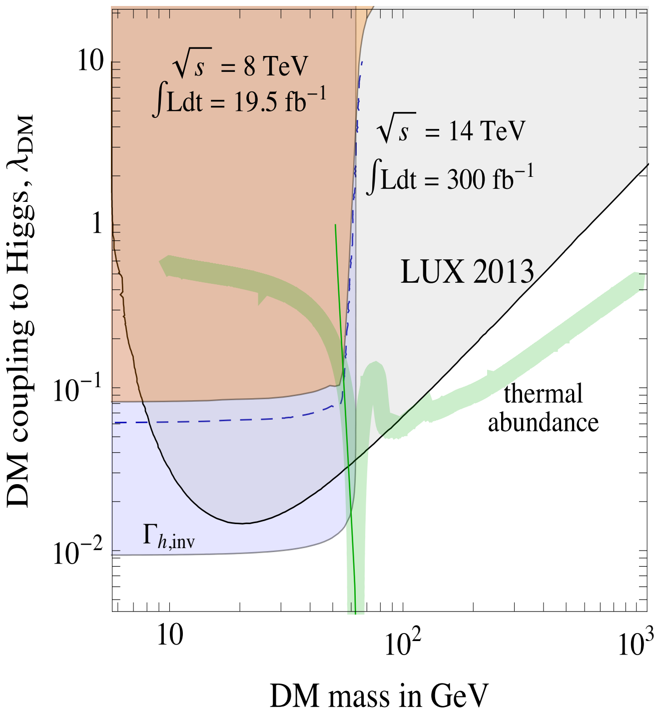


Simple models severely constrained

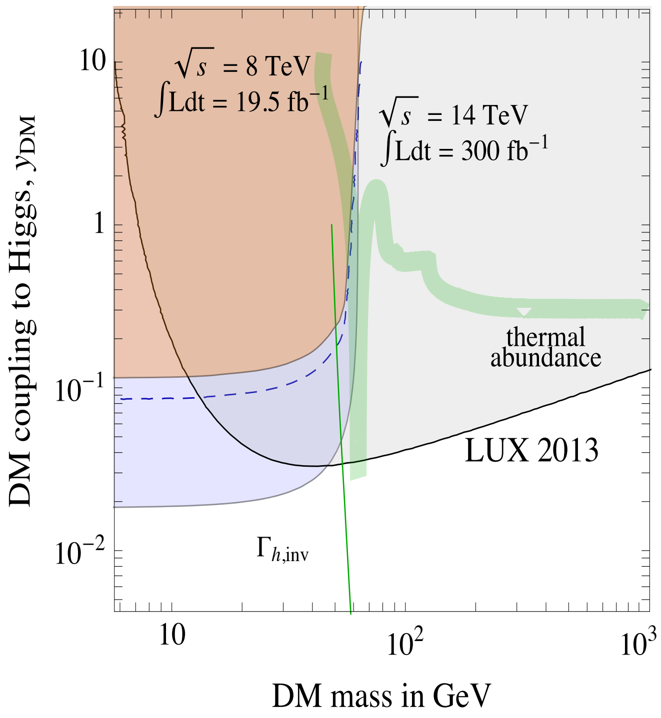
e.g. Minimal Higgs-portal DM

$$\mathcal{L} = -H^\dagger H \left[\bar{\psi}_{\rm DM} \frac{(y_{\rm DM} + i y^P_{\rm DM}\gamma_5)}{2v} \psi_{\rm DM} + \frac{\lambda_{\rm DM}}{4} s^2_{\rm DM} \right]$$

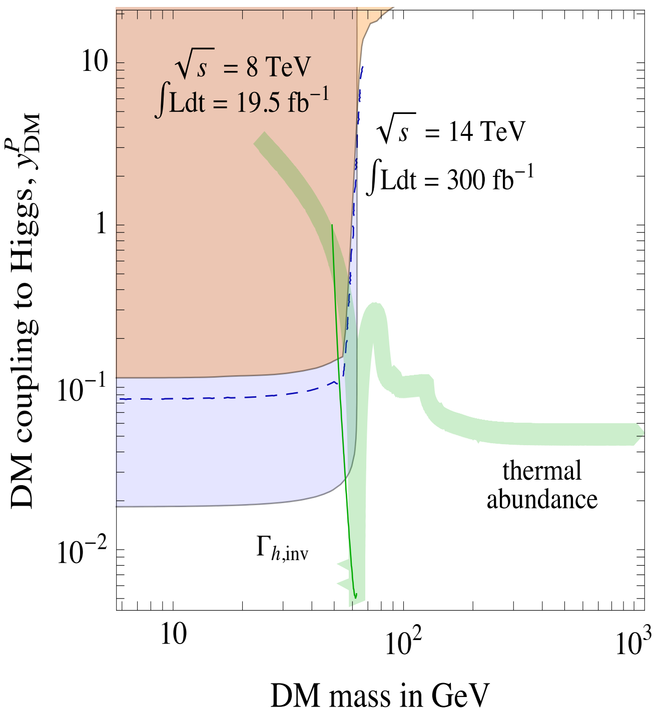
$$\mathcal{L} = -H^\dagger H\left[\bar{\psi}_{\rm DM}\frac{(y_{\rm DM}+iy^P_{\rm DM}\gamma_5)}{2v}\psi_{\rm DM}+\frac{\lambda_{\rm DM}}{4}s^2_{\rm DM}\right]$$



Scalar DM coupled to the Higgs



Fermion DM coupled to the Higgs



Fermion DM coupled to the Higgs

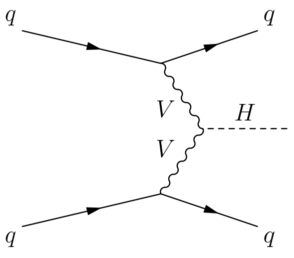
🟥 ATLAS monojet searches

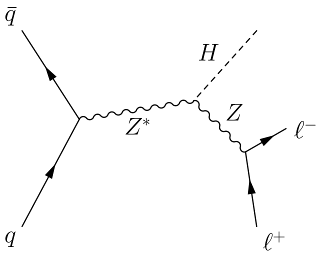
🟦 $\Gamma_{h,inv}/\Gamma_h < 20\%$

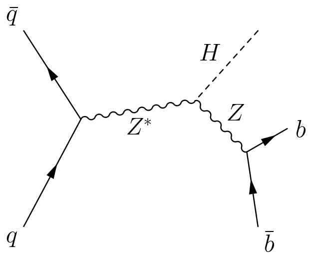
De Simone et al.1402.6287

Lopez-Honorez et al 1203.2064,
Djouadi et al 1205.3169, ...

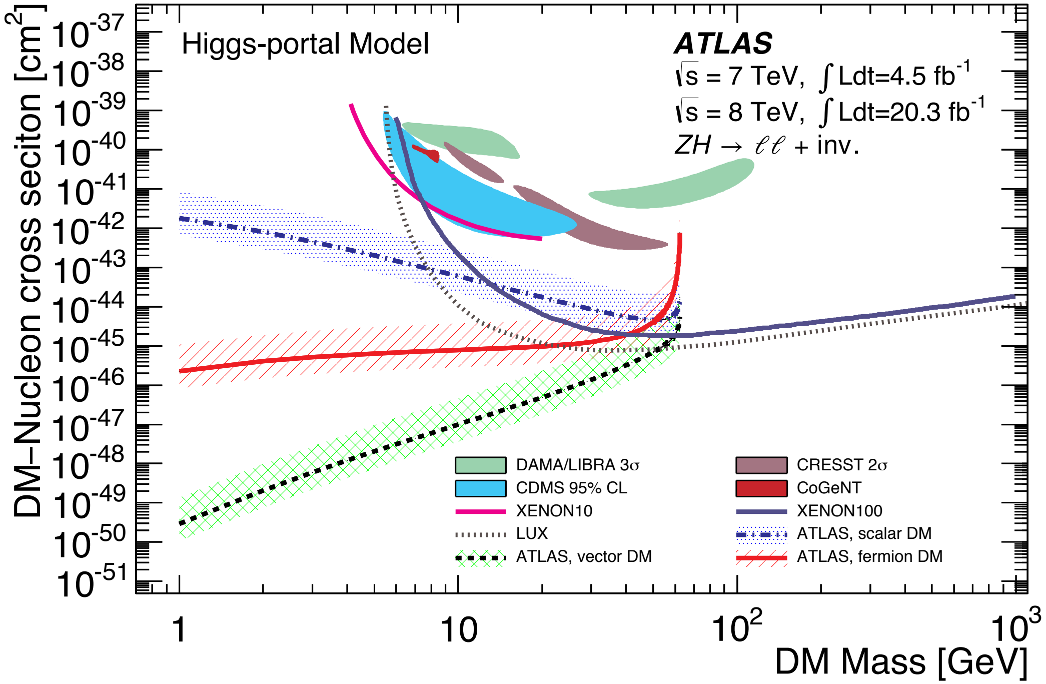
Invisible Higgs width constraints





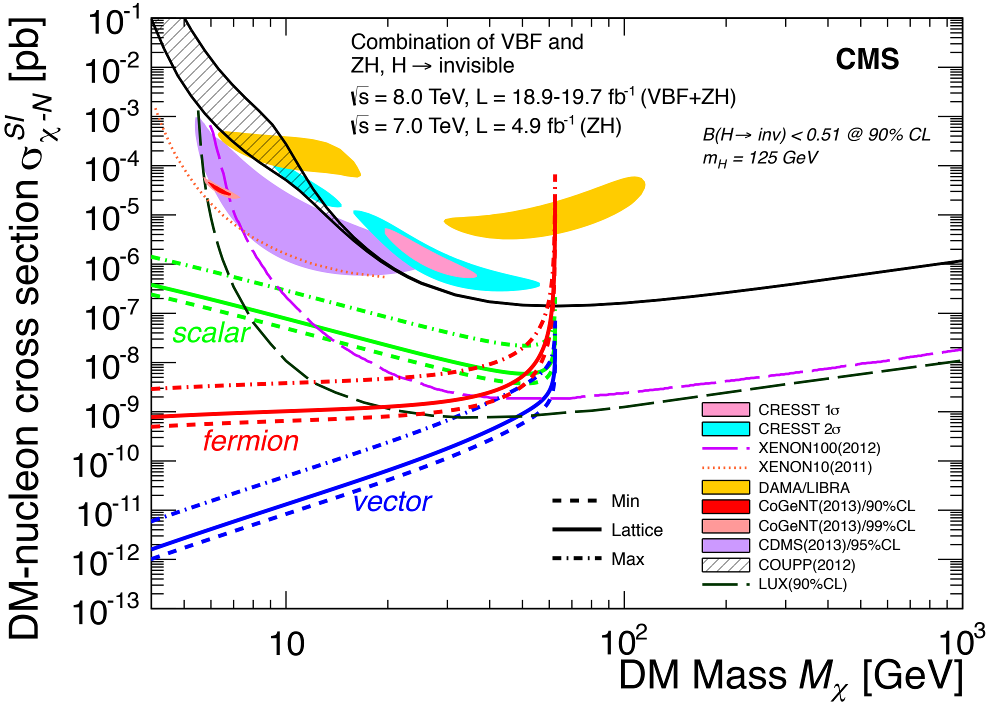


using ZH production only



$$\Gamma_{h,inv}/\Gamma_h < 75\% \quad @ \quad 95\%$$

using VBF and ZH production



$$\Gamma_{h,inv}/\Gamma_h < 58\% \quad @ \quad 95\%$$

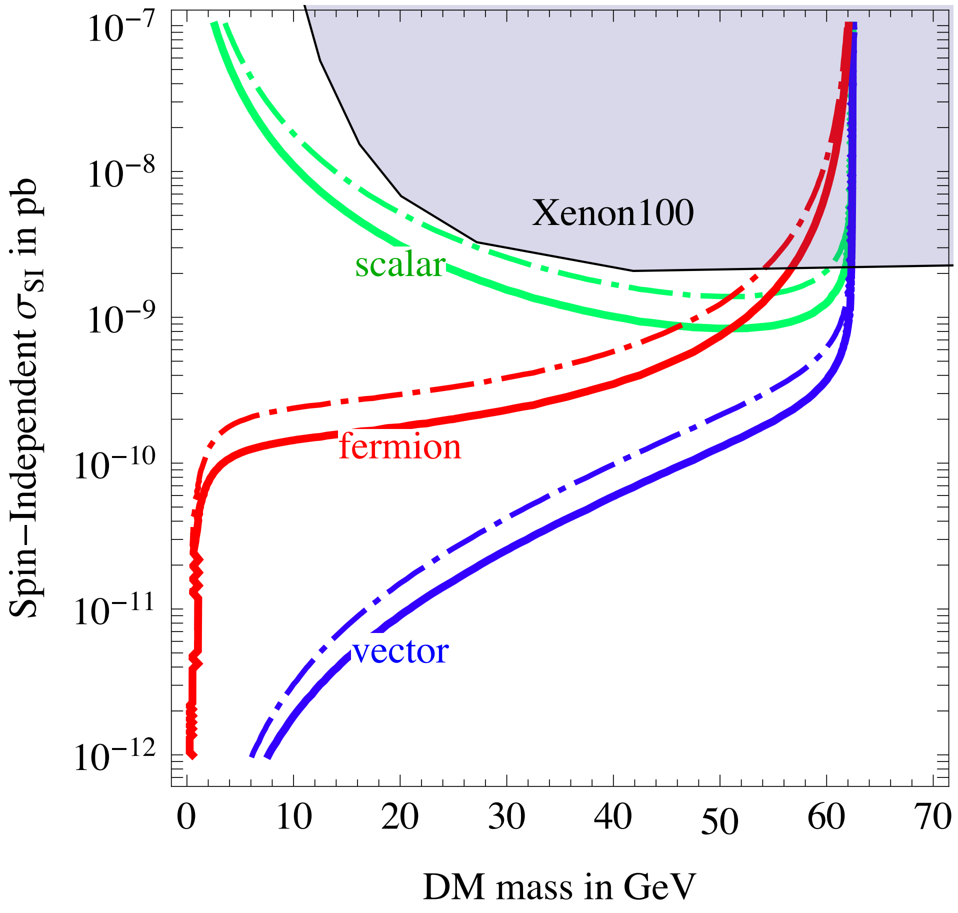
Bound on invisible Higgs width from global fit of Higgs data

The bound on the invisible Higgs boson decay width constrains the DM elastic scattering cross section on nucleons for DM candidates with masses below $M_h/2$

from global fit:

$BR_{inv} < 0.19$ (solid line)

$BR_{inv} < 0.28$ (dot-dashed)



from Giardino et al, 1303.3570

Next to minimal Higgs-portal DM

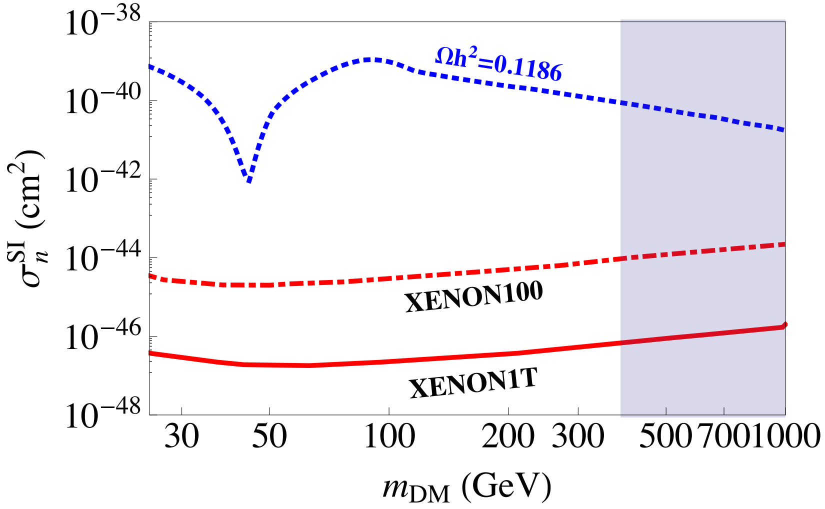
(no 2-body invisible higgs decay but h-> DM DM Z)

Greljo et al.1309.3561

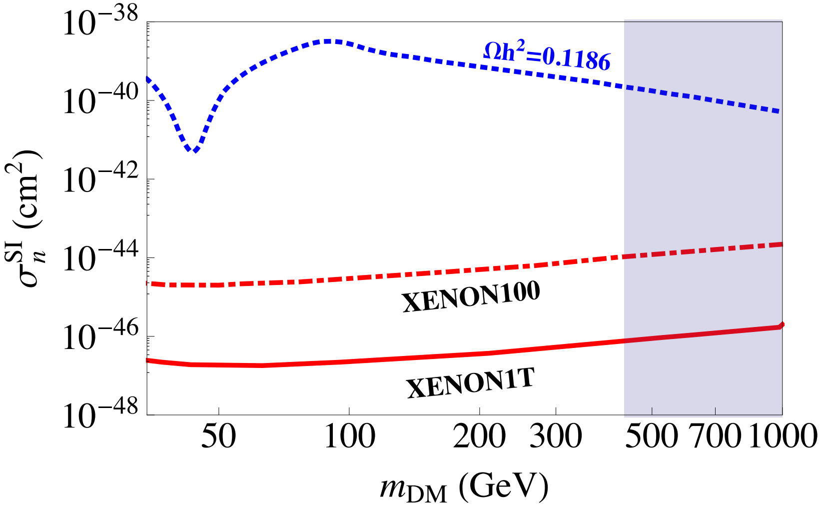
$$\mathcal{H}^0_{\rm eff} = \frac{c_\phi}{\Lambda^2} H^\dagger \overleftrightarrow{D}_\mu H \times \phi^\dagger \overleftrightarrow{\partial}^\mu \phi$$

$$\mathcal{H}^1_{\rm eff} = \frac{c_V}{\Lambda^2} i H^\dagger \overleftrightarrow{D}_\nu H \times V_\mu \overleftrightarrow{\partial}^\nu V^\mu$$

Scalar DM (c_ϕ=1)

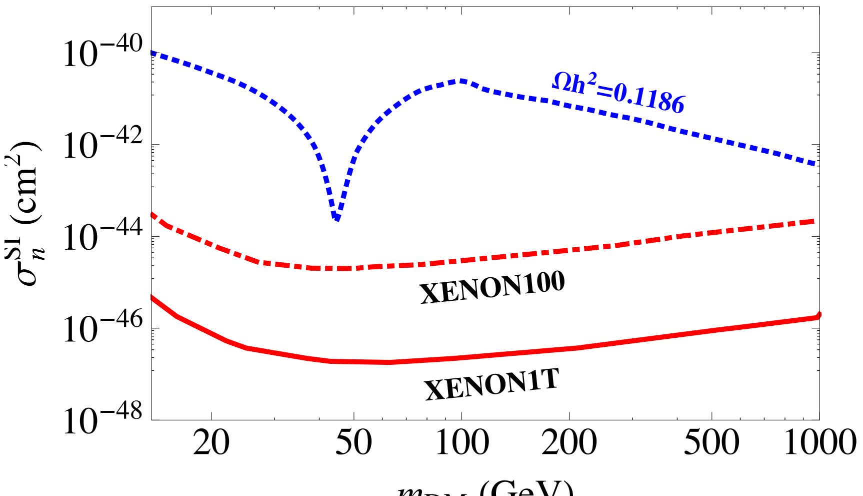


Vector DM (c_V=1)

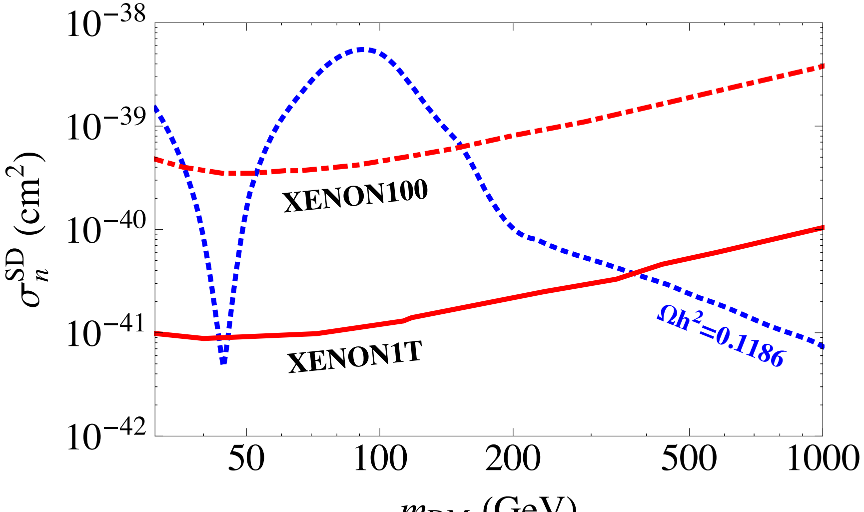


$$\mathcal{H}^{1/2}_{\rm eff} = \frac{c^V_\psi}{\Lambda^2} iH^\dagger \overleftrightarrow{D}_\mu H \times \bar\psi\gamma^\mu\psi + \frac{c^A_\psi}{\Lambda^2} iH^\dagger \overleftrightarrow{D}_\mu H \times \bar\psi\gamma^\mu\gamma_5\psi$$

Fermionic DM (c^V_ψ=1, c^A_ψ=0)

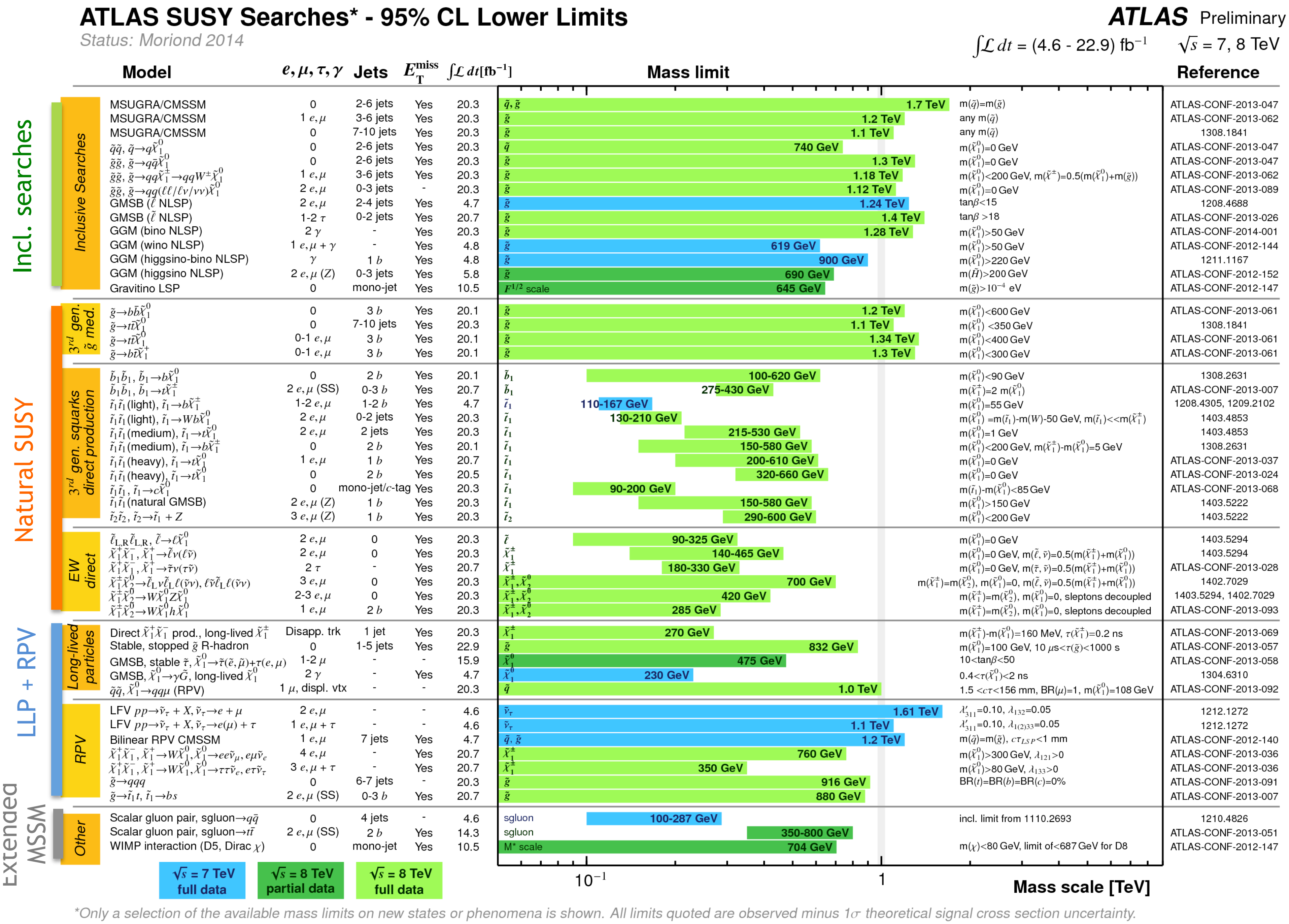


Fermionic DM (c^A_ψ=1, c^V_ψ=0)



one can do the same exercise with other simple minimal DM models with Z-mediator, Z’ mediator...

SUSY DM



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt$[fb^{-1}]	Mass limit		Reference
MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any m($\tilde{q}$)	1308.1841
$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m($\tilde{H}$)>200 GeV	ATLAS-CONF-2012-152
Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	m($\tilde{g}$)>10^{-4} eV	ATLAS-CONF-2012-147
$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 275-430 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$)	1403.4853
$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-200 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	ATLAS-CONF-2013-068
$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1403.5294
$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-028
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 700 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1402.7029
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 420 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 285 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	ATLAS-CONF-2013-069
Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	ATLAS-CONF-2013-057
GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q},\tilde{g}$ 1.2 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

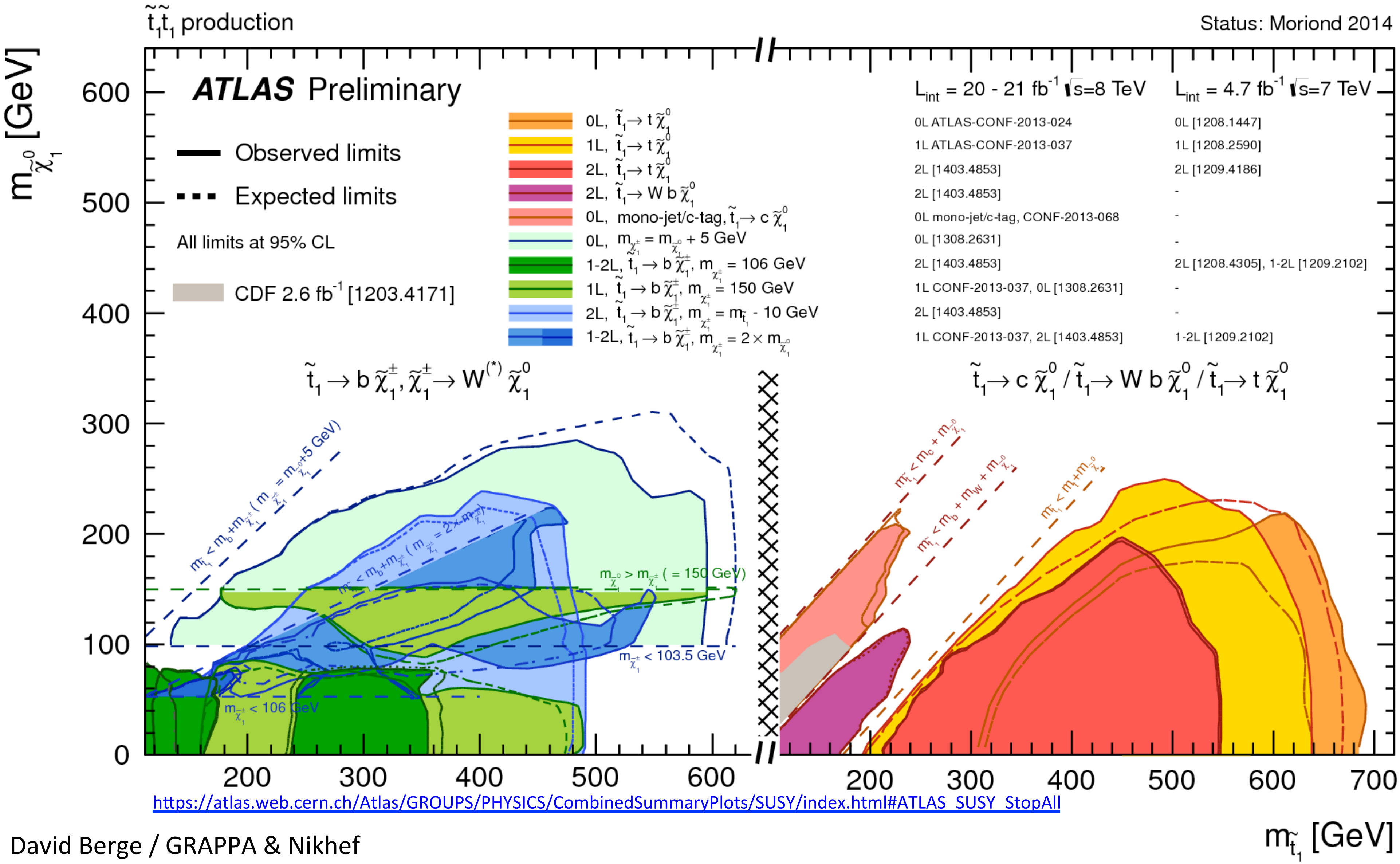
- 🟦 $\sqrt{s}$ = 7 TeV full data
- 🟩 $\sqrt{s}$ = 8 TeV partial data
- 🟩 $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Natural SUSY searches

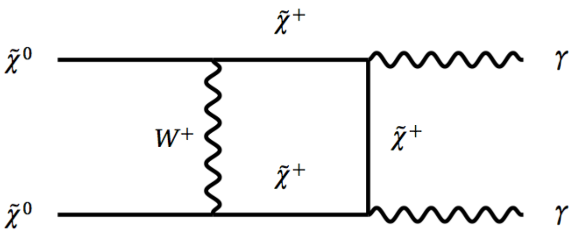
Search for 3rd generation squarks, leptons, b-jets, jets, missing Et

Probe SUSY as solution to the hierarchy problem

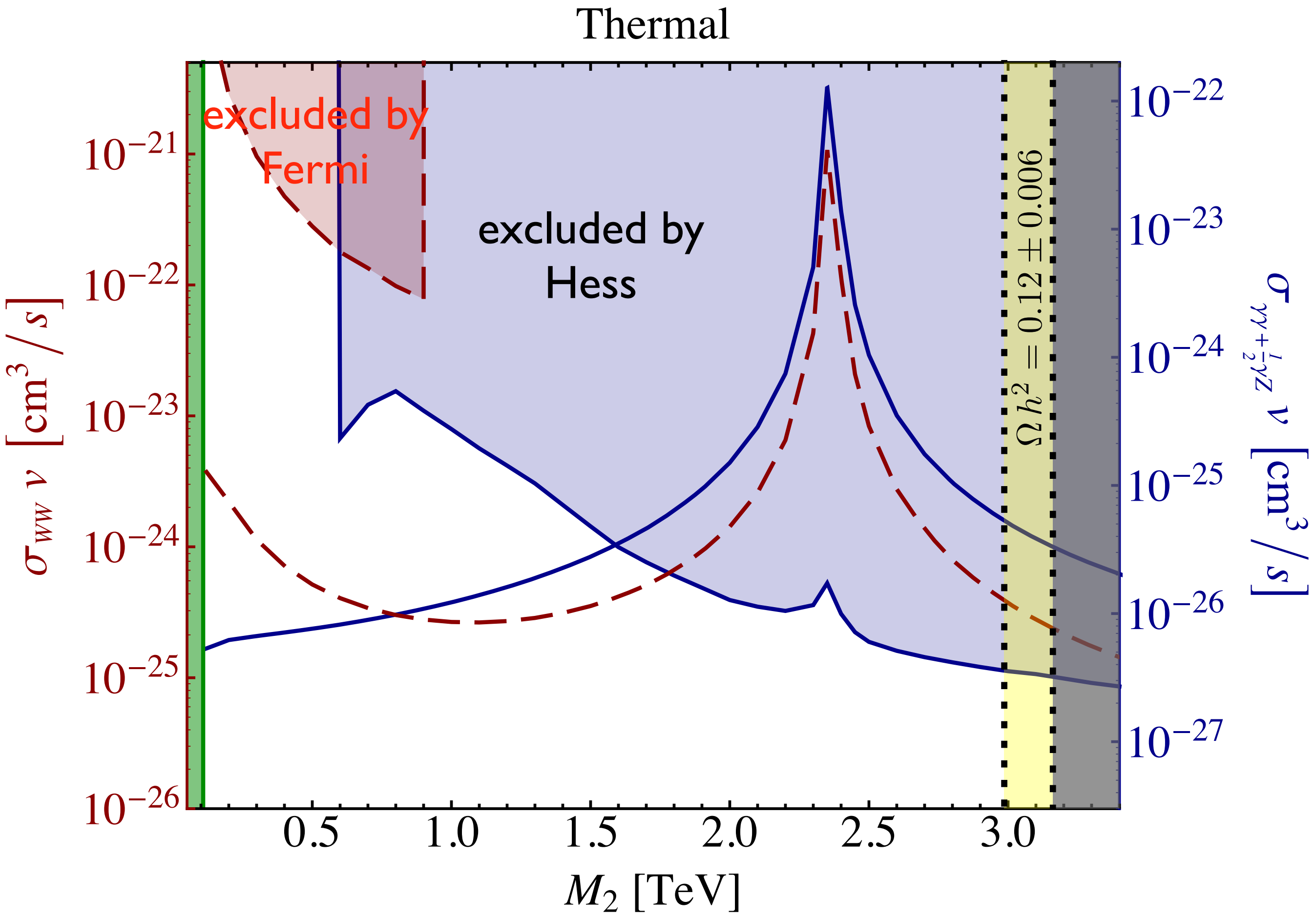


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/index.html#ATLAS_SUSY_StopAll

Wino dark matter under siege



1307.4082, Cohen et al.
1307.4400, Fan & Reece.



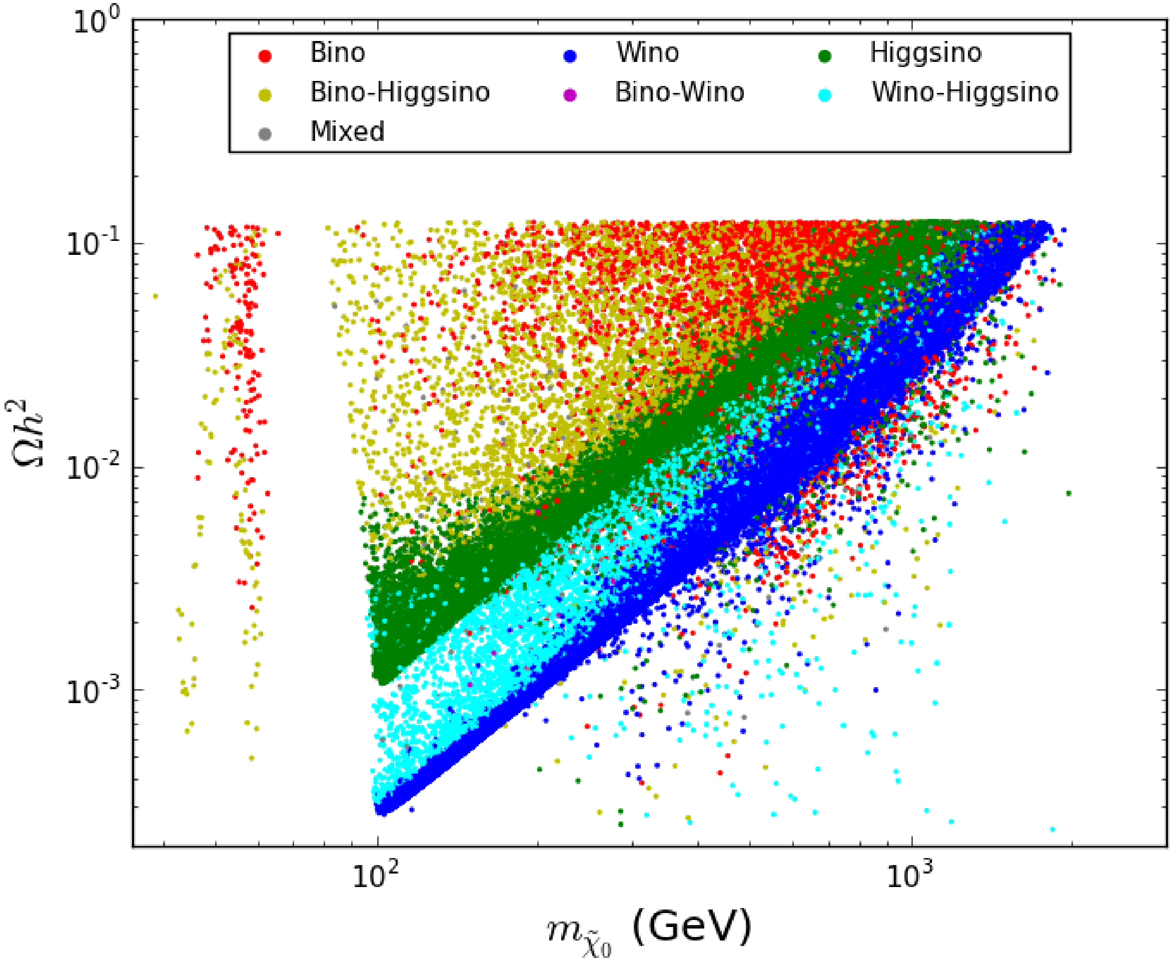
MSSM neutralino

1402.5870, Rizzo.

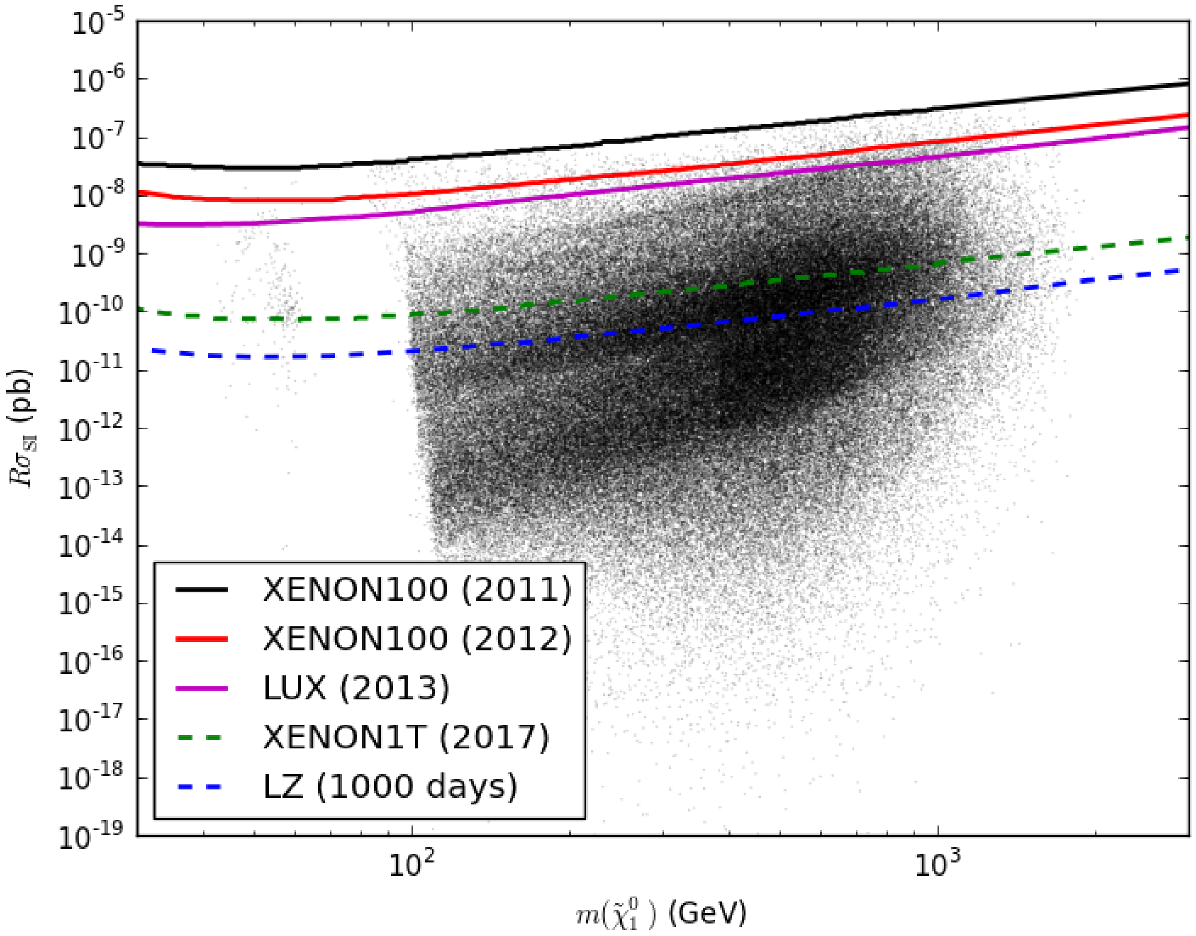
Rizzo's experiment:

- restricts to the 19-parameter MSSM
- generates many millions of model points
- subjects each of these to collider, flavor, EW precision, DM and theoretical constraints

-> 225k models survive:



- Applies direct detection constraints:



- Applies indirect detection constraints

- Applies LHC constraints

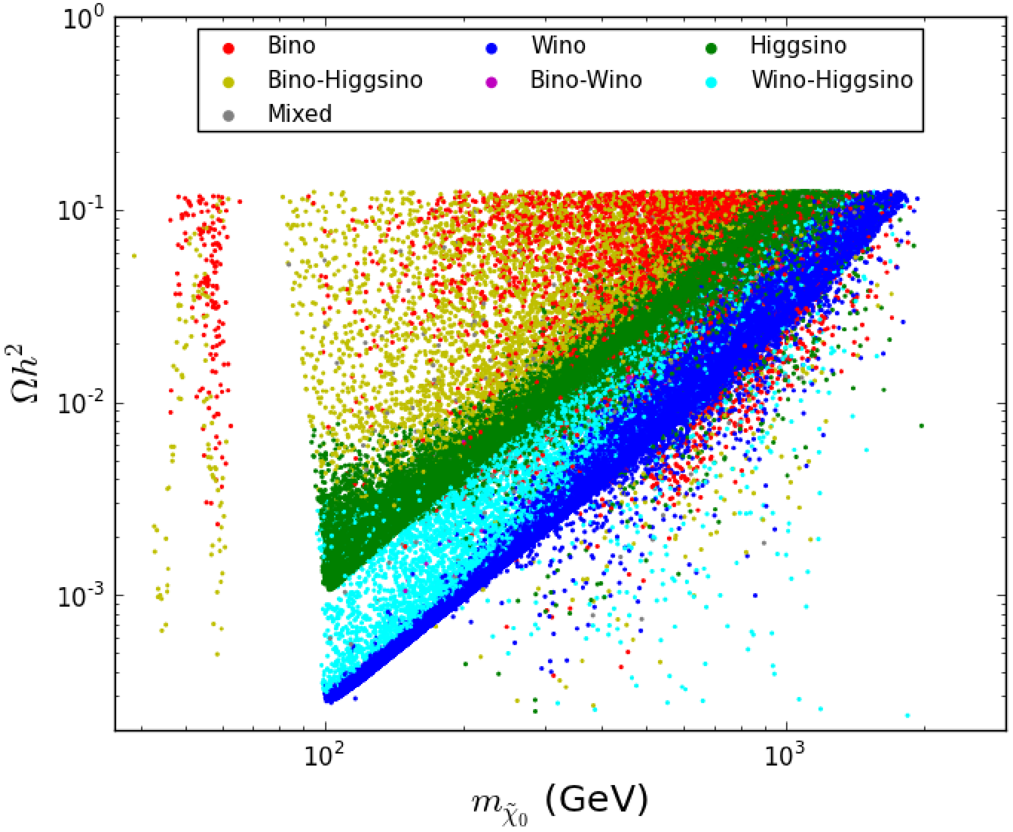
MSSM neutralino

1402.5870, Rizzo.

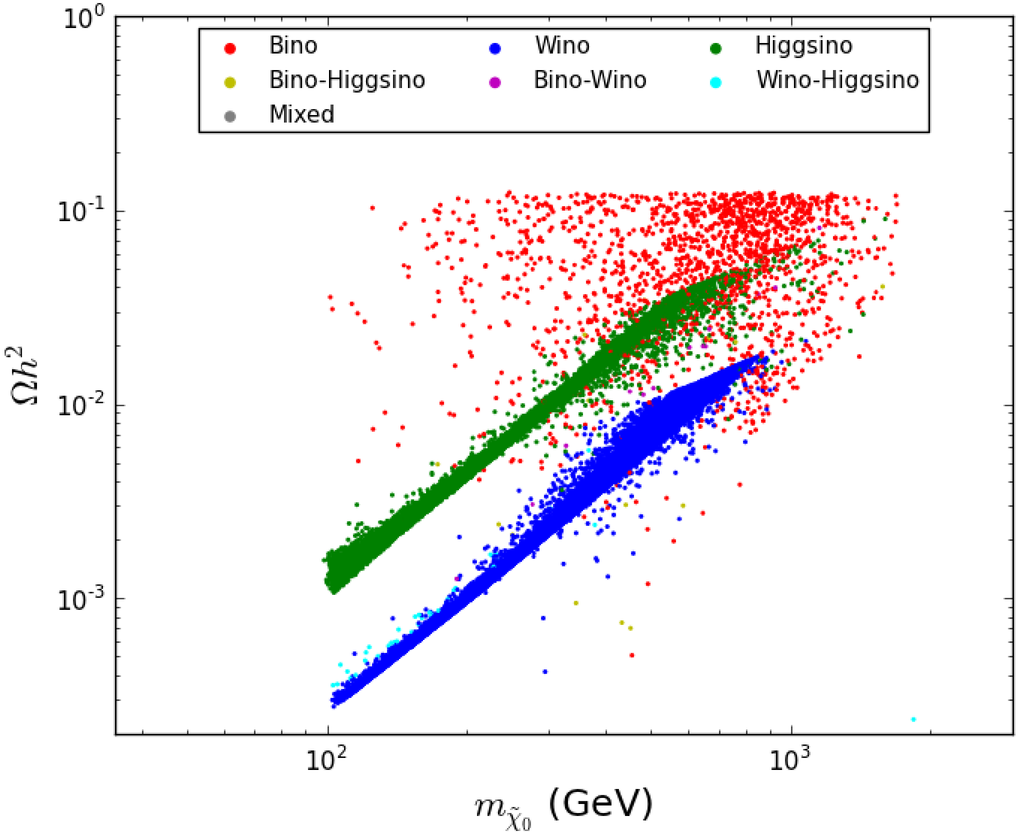
Combining direct, indirect and LHC searches

~ 75.5% of the models have been excluded by at least one of the searches

before



after



Conclusion: Parameter space of WIMP theories significantly affected after combining direct, indirect and LHC searches

A wimp which has survived the slaughter (so far) :

The KK photon in minimal Universal Extra dimensions
has essentially remained untouched since its original proposal.

hep-ph/0206071,
hep-ph/0209262

Status of Kaluza-Klein Dark Matter in models of Universal Extra Dimensions

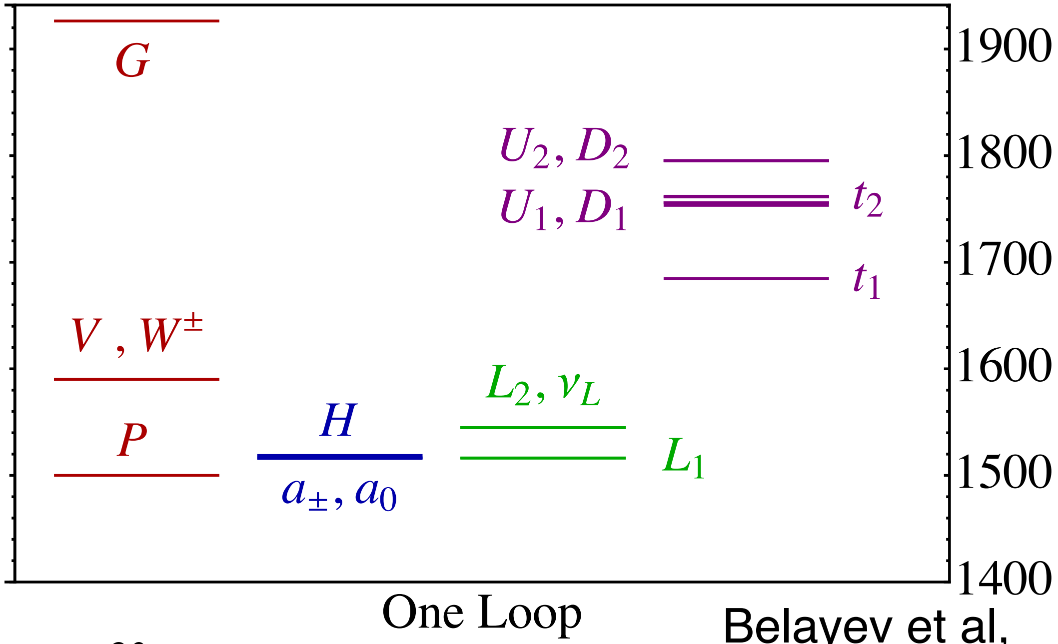
1401.4176

Universal Extra Dimensions at a glance:

simplest X-dim models: SM embedded in 5D (flat)

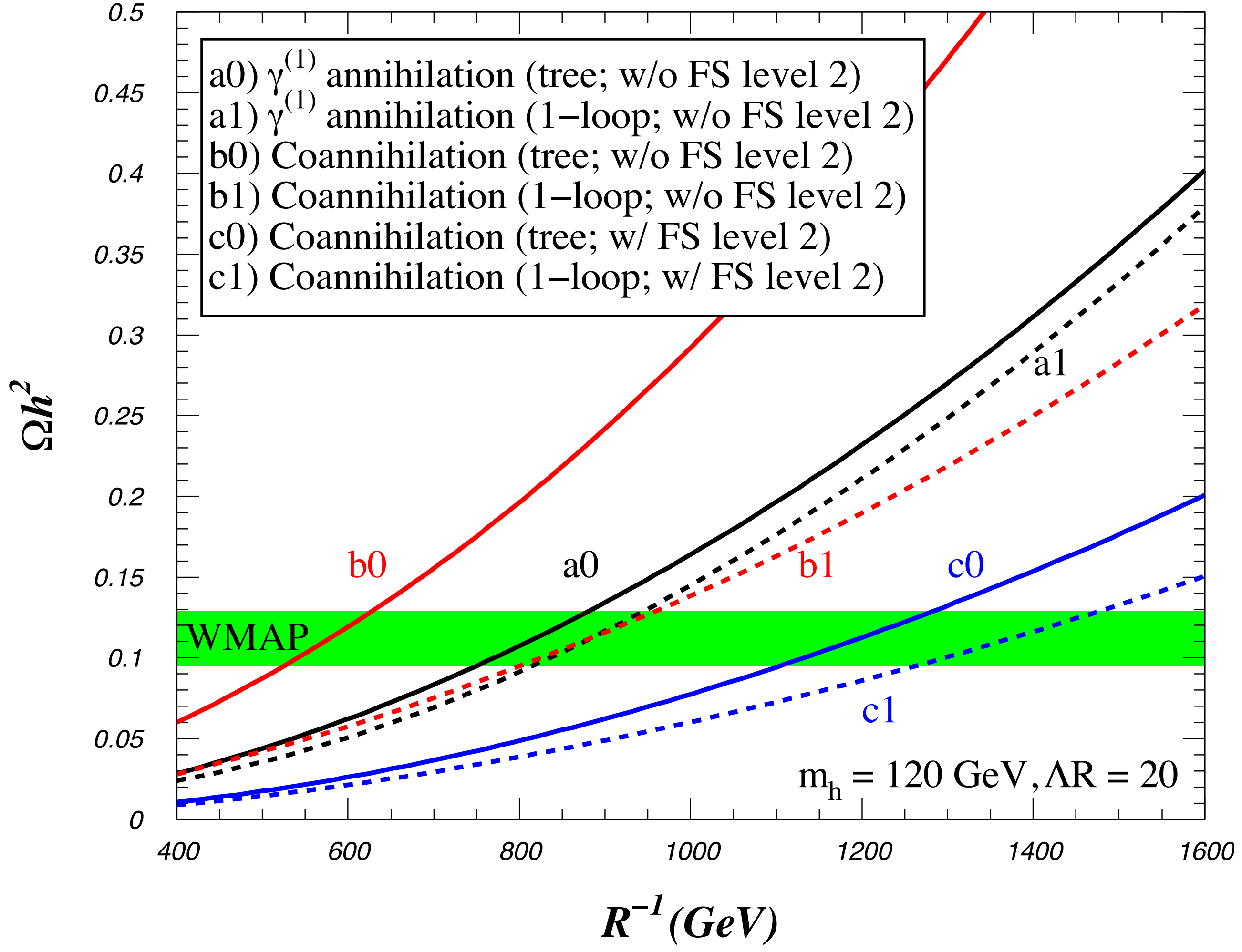
key property: boundary lagrangians respect a space-time symmetry called Kaluza-Klein parity.
As a result, the Lightest-Kaluza-Klein is stable.
Besides, Kaluza-Klein number conservation leads to weak bounds on the KK mass scale from EW precision constraints.

assuming vanishing boundary terms, the KK mass spectrum is rather degenerate:

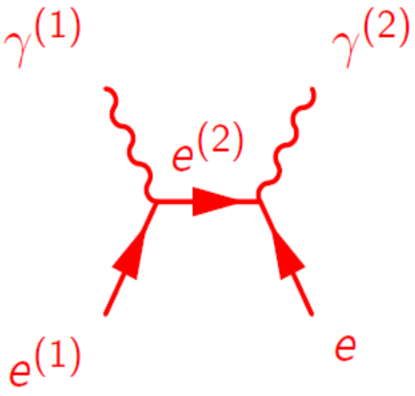


Belayev et al, 1212.4858

Relic abundance calculation, state of the art



a key-diagram:

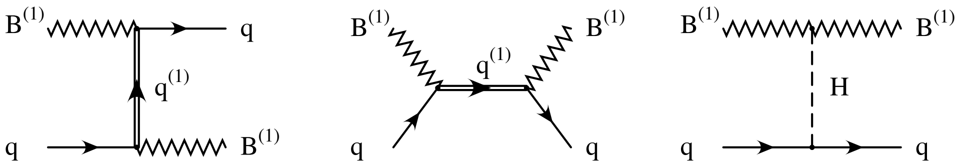


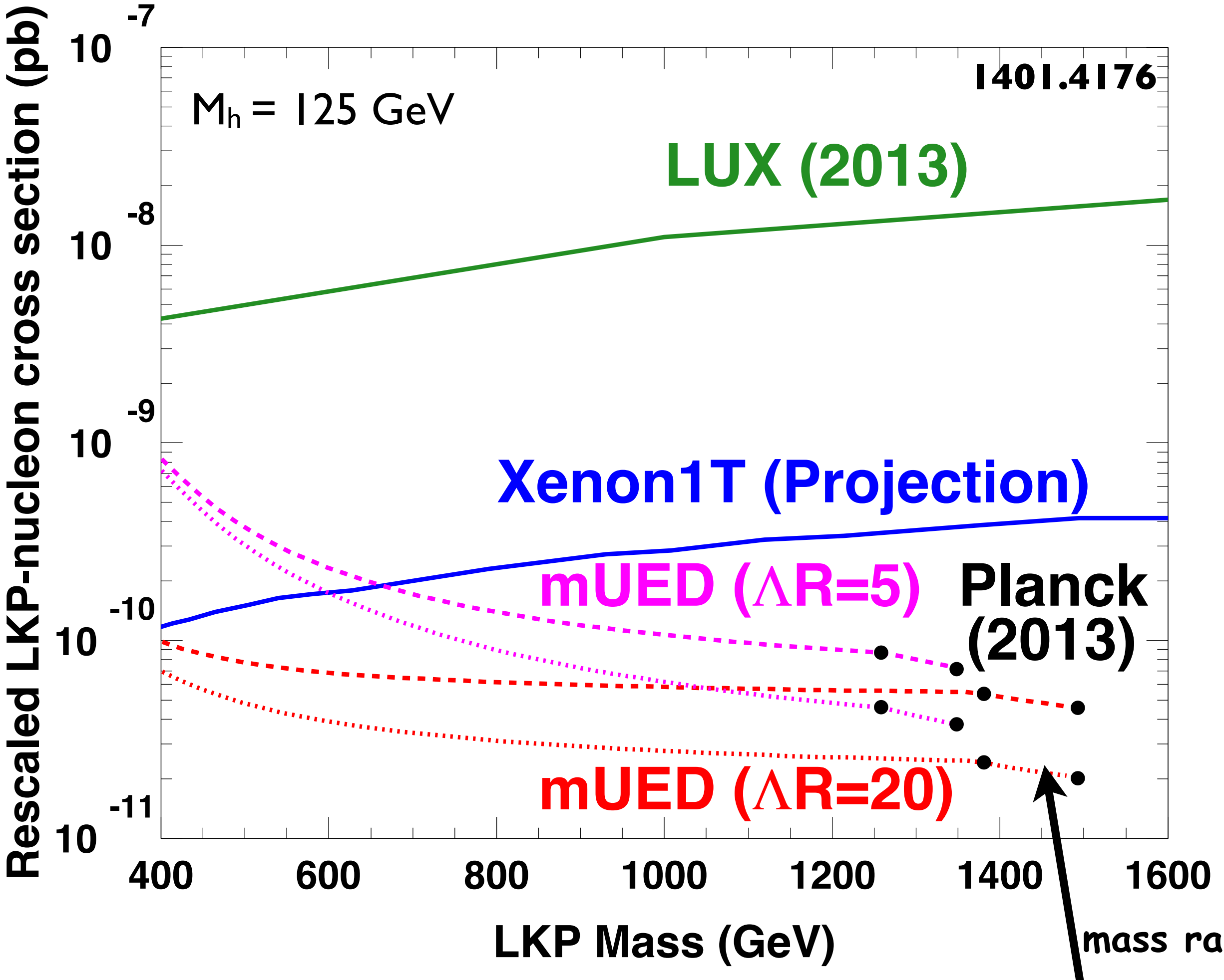
Belanger et al, 1012.2577

---> M_DM ~ 1. 4 TeV Lambda . R = 20

in this mass range, no constraint from direct detection nor indirect detection

Direct detection: not very promising

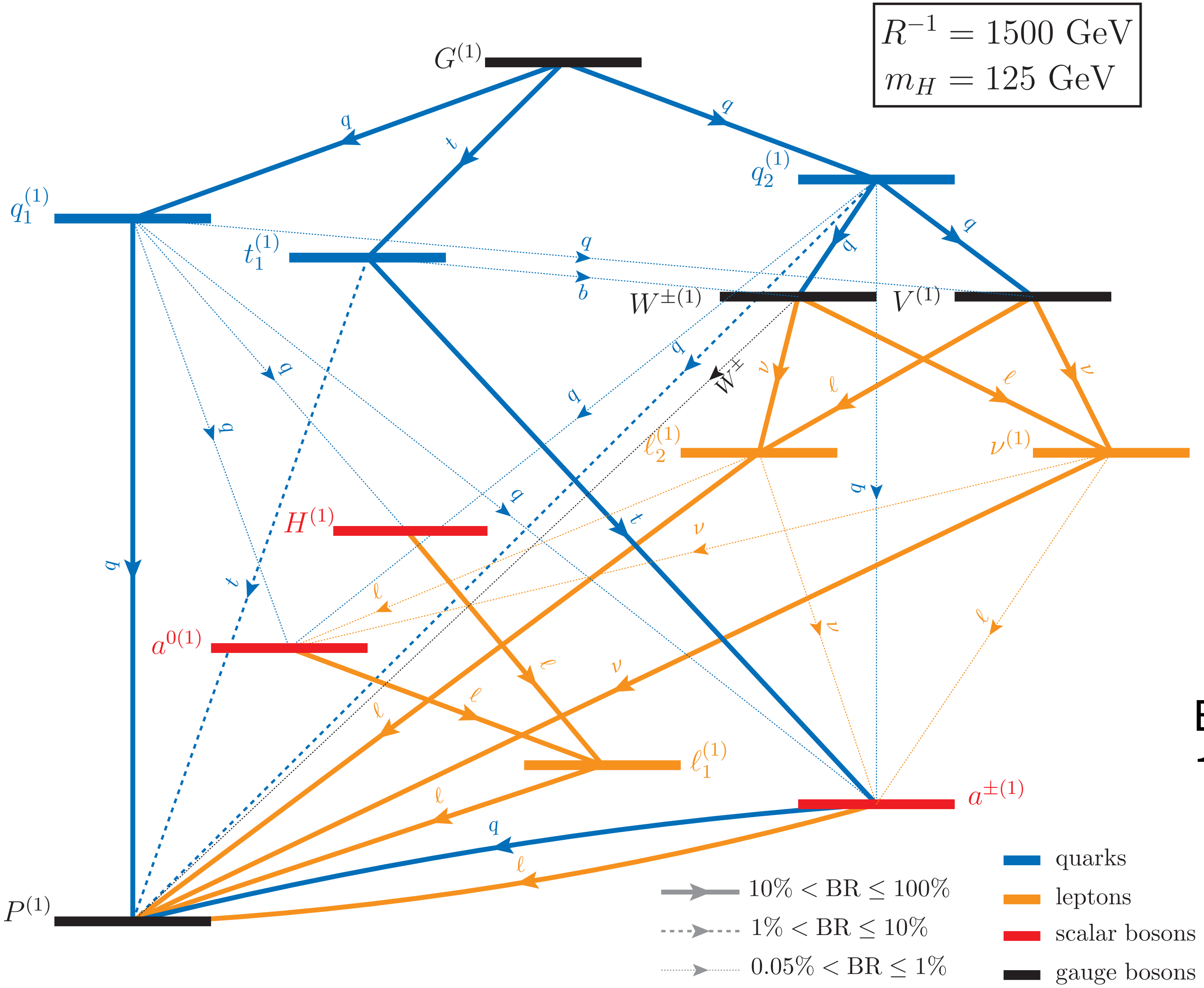




mass range with correct relic abundance

LHC searches

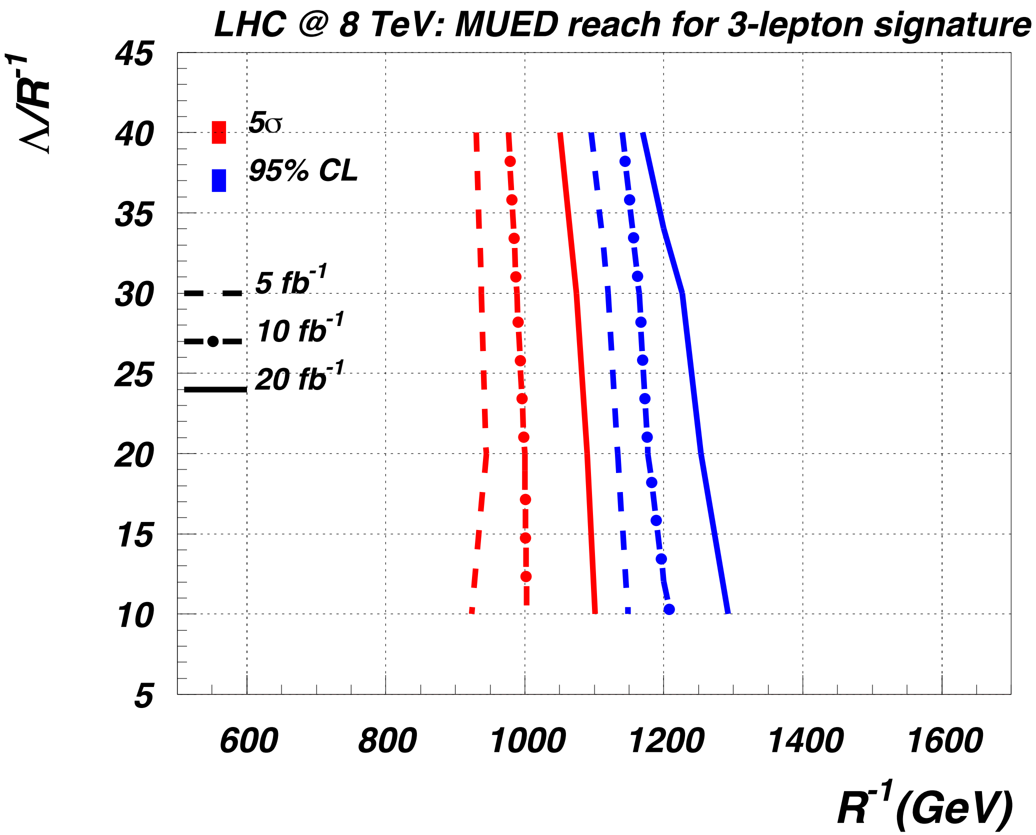
production of KK quarks and gluons, that decay into multi-lepton patterns



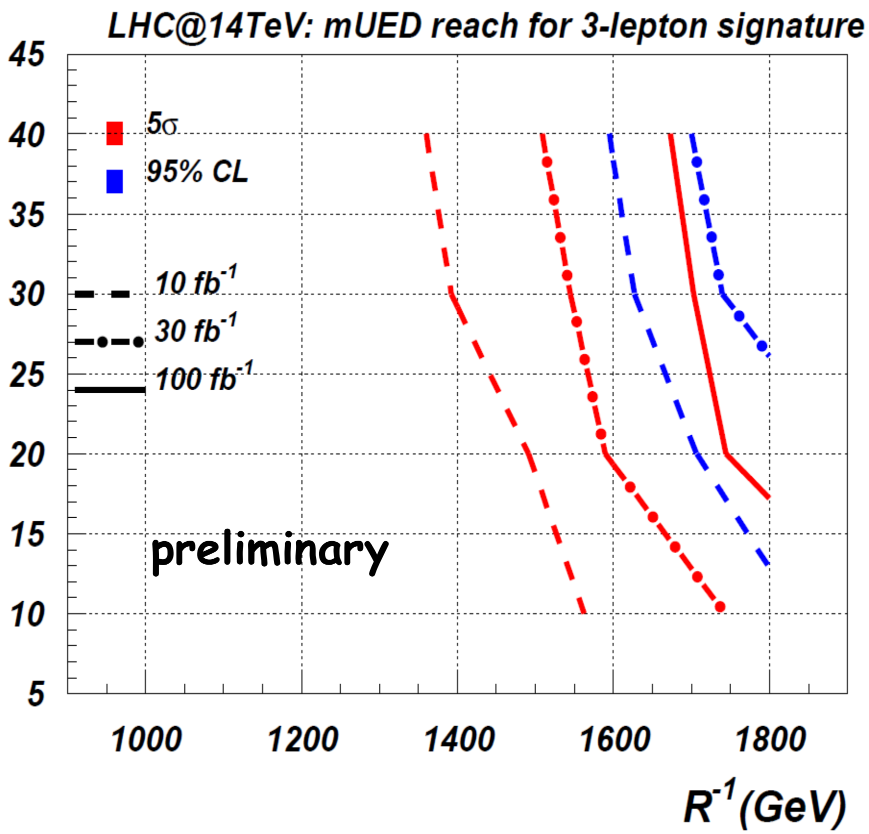
Belayev et al,
1212.4858

LHC bounds and prospects

Best prospects in the 3-lepton channel (no official ATLAS or CMS analysis). The 8 TeV expected to exclude up to M_KK~ 1.2 TeV.



LHC @ 8 TeV: MUED reach for 3-lepton signature



LHC@14TeV: mUED reach for 3-lepton signature

Belayev et al, 1212.4858

Range relevant for DM will be probed in the 14 TeV run. (but will be more difficult for low Lambda.R values)

1401.7050

Reminder to the younger part of the audience:

Wimps were not invented to solve the DM puzzle.

Wimps were predicted as part of the spectrum
of natural theories...

As of today, the logic has been reversed.
Which theorists still follow naturalness as a guiding principle?

Model building beyond the Standard Model: “historical” overview

Big hierarchy addressed

SUSY
[70 ies to now]

R-parity→ LSP

ADD (large extra dim)
[98-99]

RS (Randall-Sundrum)
[99 to now]

the attitude:
Naturalness is what matters, dark matter is a secondary issue

……

Little hierarchy addressed

UED
[2001 to now]

KK-parity→ LKP
[2002]

Little Higgs
[2002-2004]

T-parity→ LTP
[2003]

Lower your ambition (no attempt to explain the M_{EW}/M_{Pl} hierarchy); rather put a ~ TeV cutoff

……

Big & little hierarchy pbs ignored

“Minimal” SM extensions
[2004 to now]

assume discrete symmetry, typically a Z_2

Give up naturalness, focus on dark matter and EW precision tests. Optional: also require unification

New symmetries at the TeV scale and Dark Matter

the ~ 2000-2004 approach:

to cut-off quadratically divergent quantum corrections to the Higgs mass

New TeV scale physics needed

tension with precision tests of the SM in EW & flavor sector (post-LEP "little hierarchy pb")

introduce new discrete symmetry P

R-parity in SUSY, KK parity in extra dim, T parity in Little Higgs ...

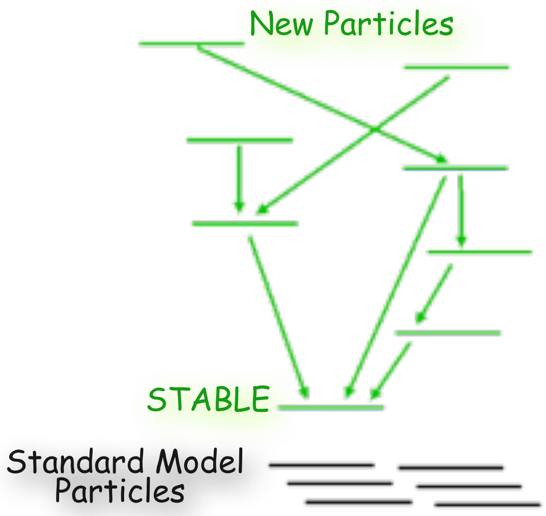
Lightest P-odd particle is stable

DM candidate

Work out properties of new degrees of freedom

The stability of a new particle is a common feature of many models

mass spectrum,
interactions



dark matter candidates

relic abundance

detection signatures & rates

Dark matter theory

dark matter model building until ~2004: mainly theory driven

largely motivated by hierarchy pb:
SUSY+R-parity,
Universal Extra Dimensions + KK parity
Little Higgs models+ T-parity

post LEP-2--> questioning of naturalness as a motivation for new physics @ the Weak scale

“minimal approach”: focus on dark matter only and do not rely on models that solve the hierarchy problem

+ various “hints” (?...):

DAMA, INTEGRAL, PAMELA, ATIC, Fermi line ...

➡ dark matter model building since ~2008: data driven
(or ambulance chasing)

Weight-philic Dark Matter

DM couples most significantly to particles with heavy masses, while couplings to light SM states are suppressed.

Simplified model inspired by framework of composite Higgs and Top quarks

Higgs scalars as pseudo-Nambu-Goldstone bosons of new dynamics above the weak scale

New strong sector endowed with a global symmetry G spontaneously broken to H → delivers a set of Nambu Goldstone bosons

global symm. on u,d

strong int.

QCD: $SU(2)_L \times SU(2)_R \xrightarrow[SU(3)_c]{} SU(2)_V \supset U(1)_Q$

6 - 3 = 3 PNGB $\pi^{\pm}, \pi_0$

global symm. on techniquarks

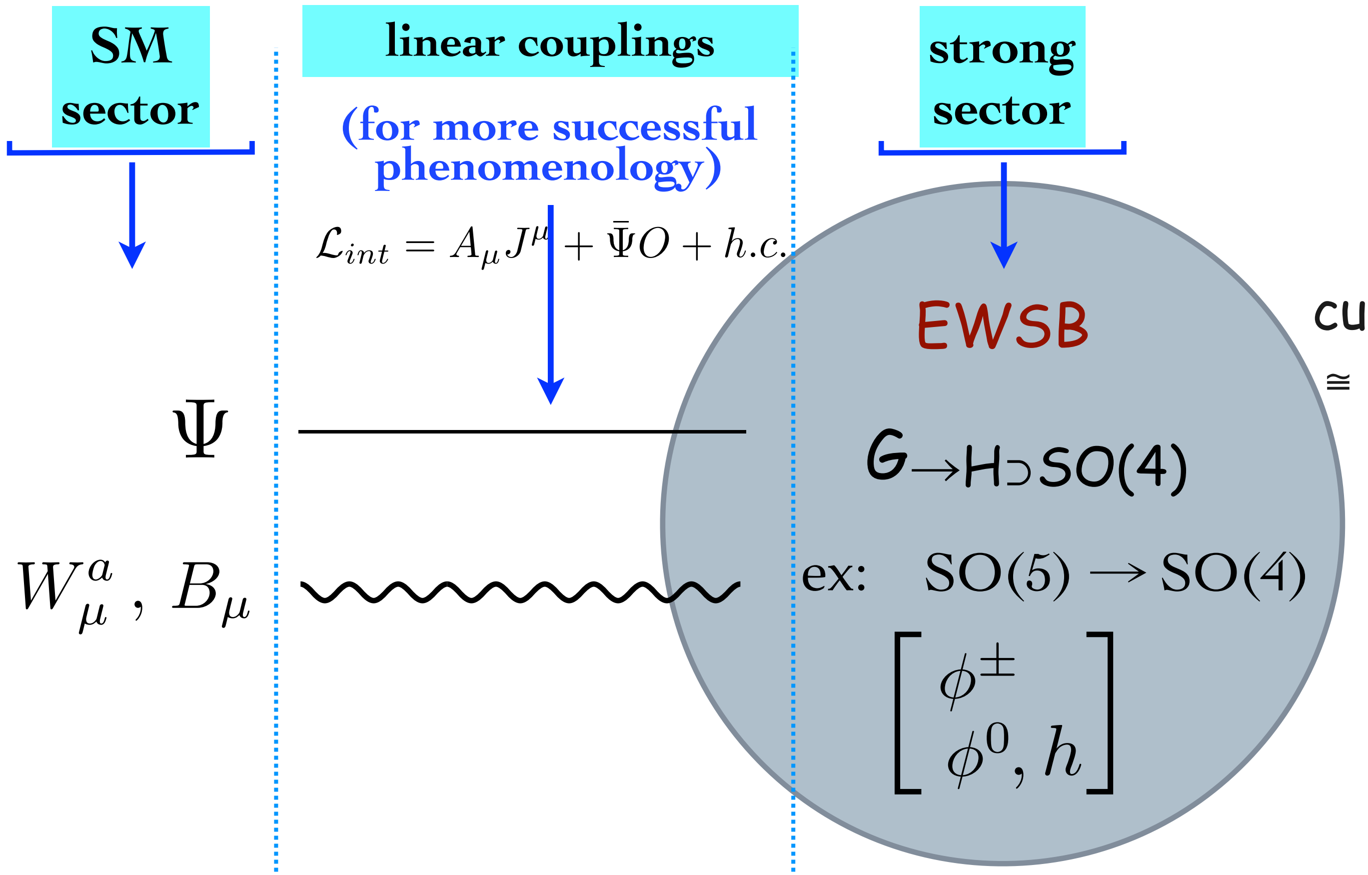
Composite Higgs: $SO(6) \times U(1)_x \xrightarrow[SU(N_c)]{} SO(5) \times U(1)_Y \supset SU(2) \times U(1)_Y$

16 - 11 = 5 PNGB H, S

SO(5)/SO(4) -> SM Higgs
SO(6)/SO(5) -> SM + Singlet
SO(6)/SO(4) -> 2 Higgs Doublet Model

associated LHC tests

General structure -> Partial compositeness



SM sector

linear couplings

(for more successful phenomenology)

$\mathcal{L}_{int} = A_\mu J^\mu + \bar{\Psi} O + h.c.$

strong sector

Ψ

$W^a_\mu \,,\; B_\mu$

EWSB

G→H⊃SO(4)

ex: $\mathrm{SO}(5) \to \mathrm{SO}(4)$

$$\begin{bmatrix} \phi^\pm \\ \phi^0, h \end{bmatrix}$$

custodial SO(4) ≅ SU(2)×SU(2)

to avoid large corrections to the T parameter

$\mathcal{L}_{elementary}$ $\mathcal{L}_{mix}$ $\mathcal{L}_{composite}$

$$\mathcal{L} = \bar{q}_L \, \not{\partial} \, q_L + \bar{t}_R \, \not{\partial} \, t_R + \Delta_L \, \bar{q}_L \, (T, B) + \Delta_R \, \bar{t}_R \tilde{T} + \mathrm{Tr}\left\{ \bar{\mathcal{Q}} \, (\not{\partial} - \underset{\mathbf{2}}{M_{\mathcal{Q}}}) \, \mathcal{Q} \right\} + \bar{\tilde{T}} \, (\not{\partial} - \underset{\mathbf{1}}{M_{\tilde{T}}}) \, \tilde{T}$$
$$+ \, Y_* \, \mathrm{Tr}\{ \bar{\mathcal{Q}} \, \mathcal{H} \} \, \tilde{T} + h.c$$

Consider models where annihilations in the early universe and annihilations today are controlled by different processes and are therefore naturally of different sizes

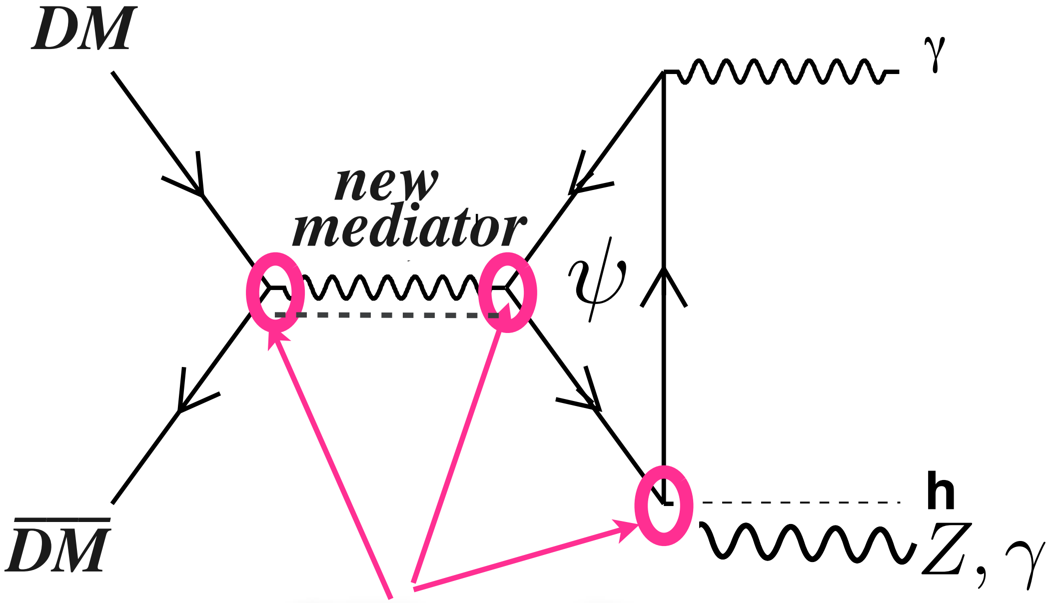
e.g. tree level annihilations not kinematically possible today, although possible in early universe if DM close in mass with other particles in new sector.

These DM theories can produce large gamma ray lines over suppressed continuum

Large gamma-ray lines, naturally: The "forbidden channel" scenario

Jackson, Servant, Shaughnessy, Tait, Taoso,'09
0912.0004 1302.1802 1303.4717

- *DM almost decouples from light SM particles while having large couplings to new heavy particles* ψ
- *$M_{DM} < M_\psi$: tree level annihilations kinematically forbidden today (DM has small velocity in our galaxy today $v/c \sim 10^{-3}$) but allowed in the early universe ($v/c \sim 10^{-1}$).*
- *Virtual* ψ *close to threshold can significantly enhance loop processes producing monochromatic photons.*



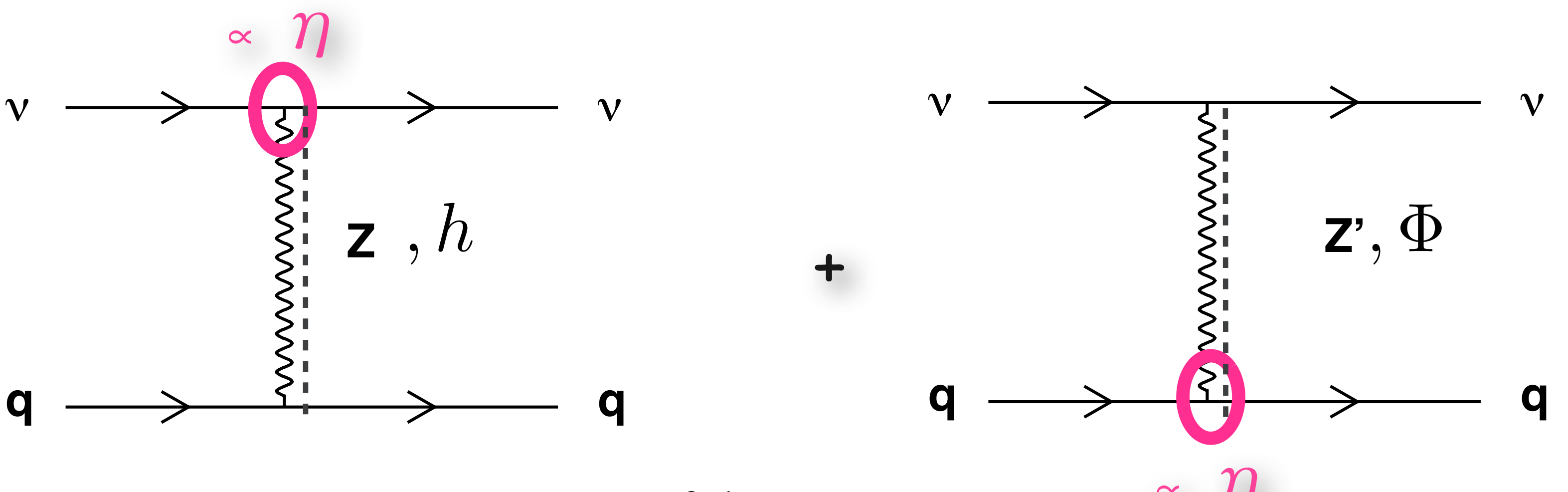
~ O(1) couplings

Advantage: elastic scattering and annihilations disconnected

0912.0004

a counter example to the simple relations derived in the effective field theory approach

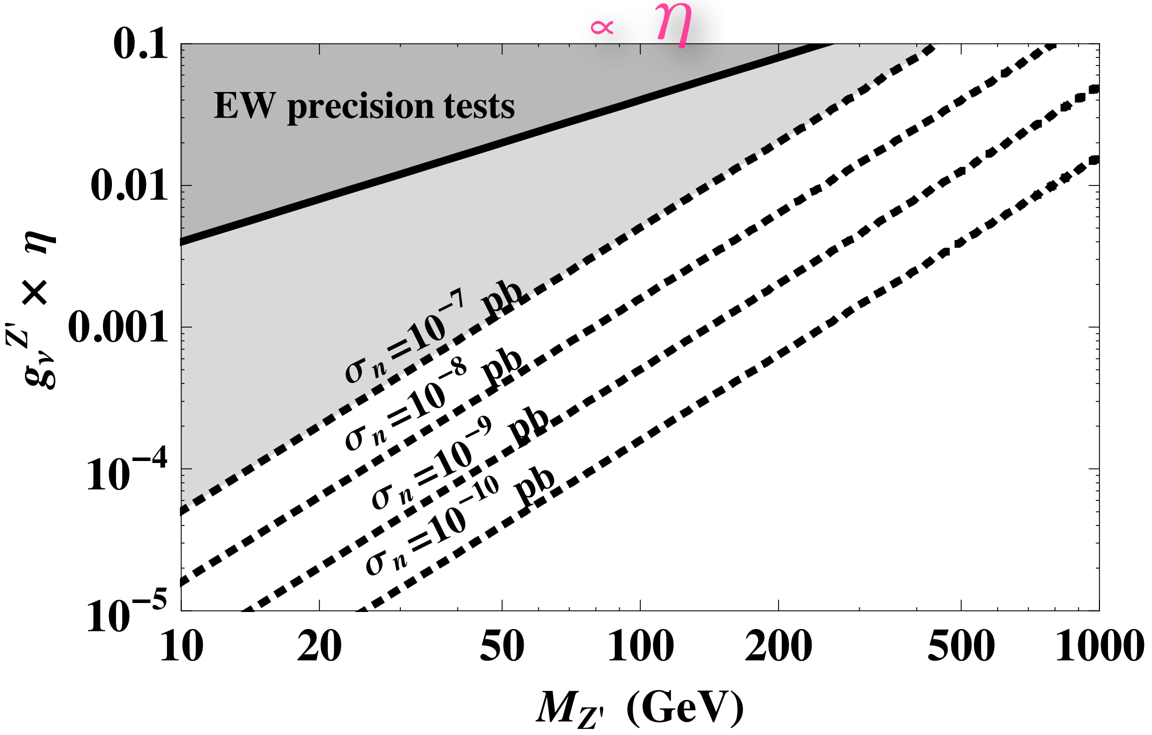
Direct detection constraints



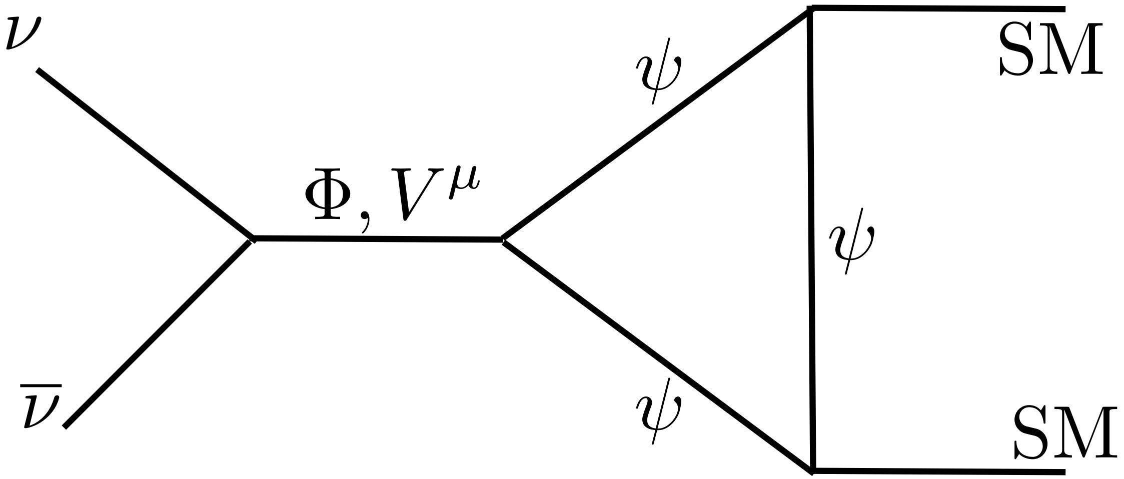
η : mixing

$\rightarrow \sigma \propto \eta^2$

ν -nucleon elastic scattering cross section contours



General topology common to all effective vertices



We want to identify the generic conditions under which large line signals occur and pay particular attention to the 1-loop continuum.

1302.1802

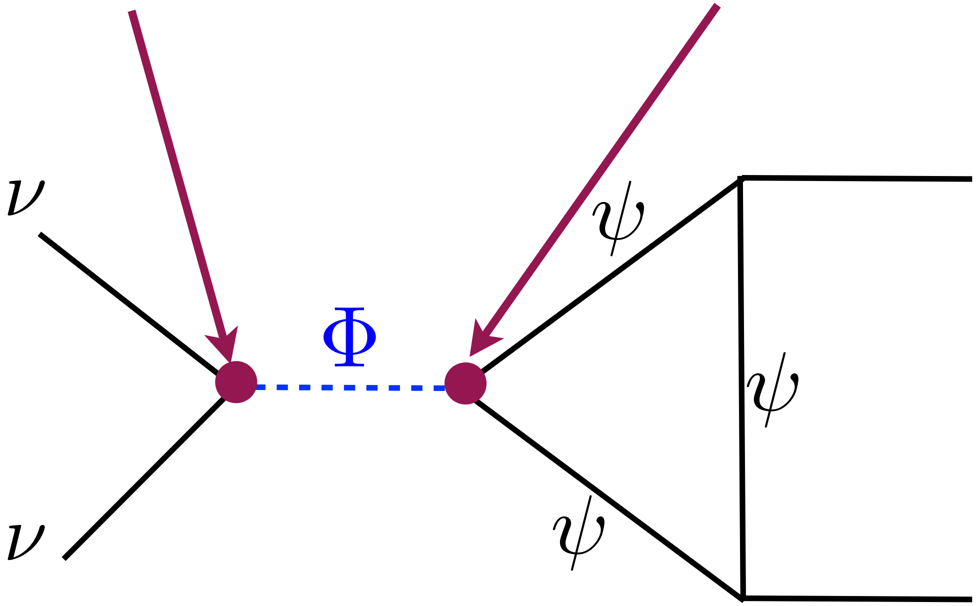
Case with scalar mediator:

Consider the very simple dark sector:

In addition to DM (ν), we add another Dirac fermion (ψ), and a real singlet (Φ) with gauge quantum numbers under $SU(3)\times SU(2)\times U(1)_Y$.

$$\nu \sim (1,1,0) \qquad \boxed{\psi \sim (1,2,1/2)} \qquad \Phi \sim (1,1,0)$$

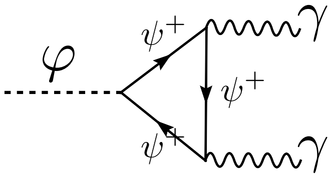
$$\mathcal{L} \supset \bar{\nu}(y^S_{\nu\Phi} + i y^P_{\nu\Phi}\gamma^5)\nu\Phi + \bar{\psi}(y^S_{\psi\Phi} + i y^P_{\psi\Phi}\gamma^5)\psi\Phi - y_H(\bar{\psi}H\nu + h.c)$$



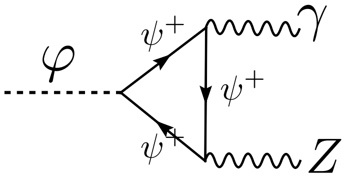
small but responsible for ψ decay

1-loop annihilation channels via scalar mediator for $\boxed{\psi \sim (1,2,1/2)}$

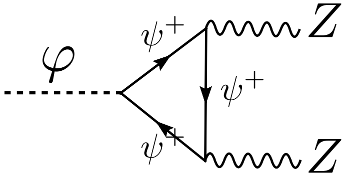
$\gamma\gamma$

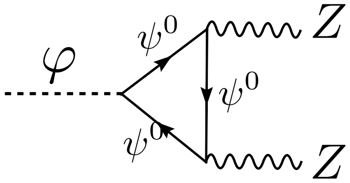


γZ

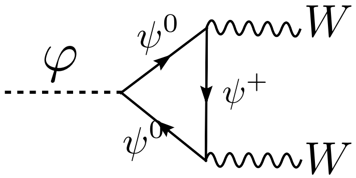


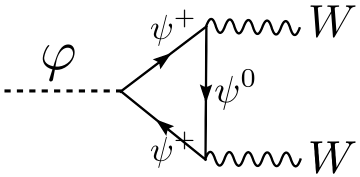
ZZ



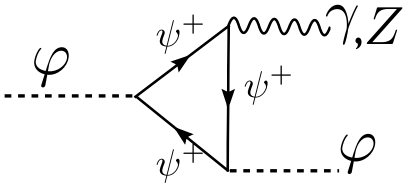


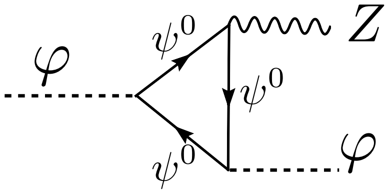
WW





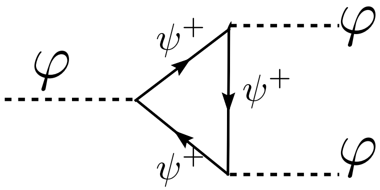
$\gamma\varphi, Z\varphi$

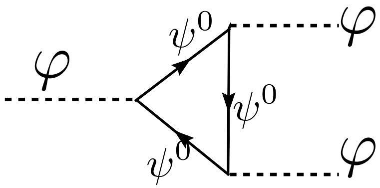




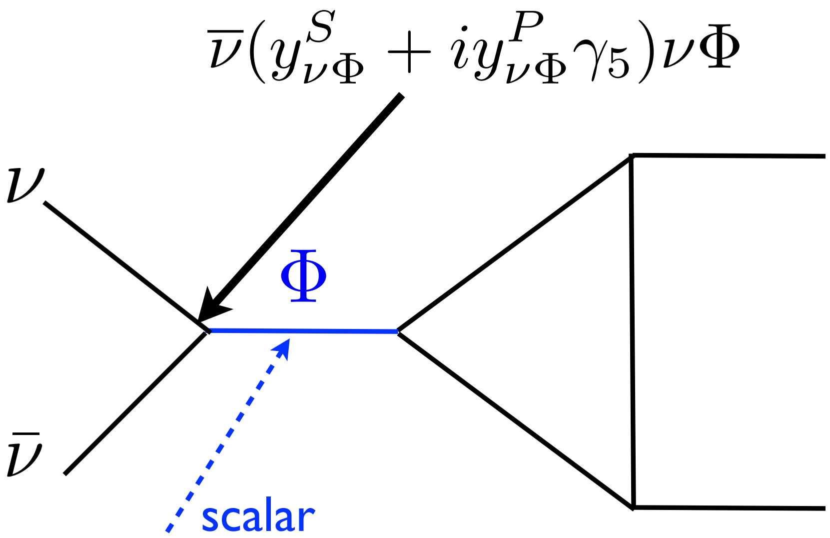
=0

$\varphi\varphi$





Case with scalar mediator:



$$\propto \left((y^S_{\nu\Phi})^2 \boxed{\beta^2} + 4(y^P_{\nu\Phi})^2\right)$$

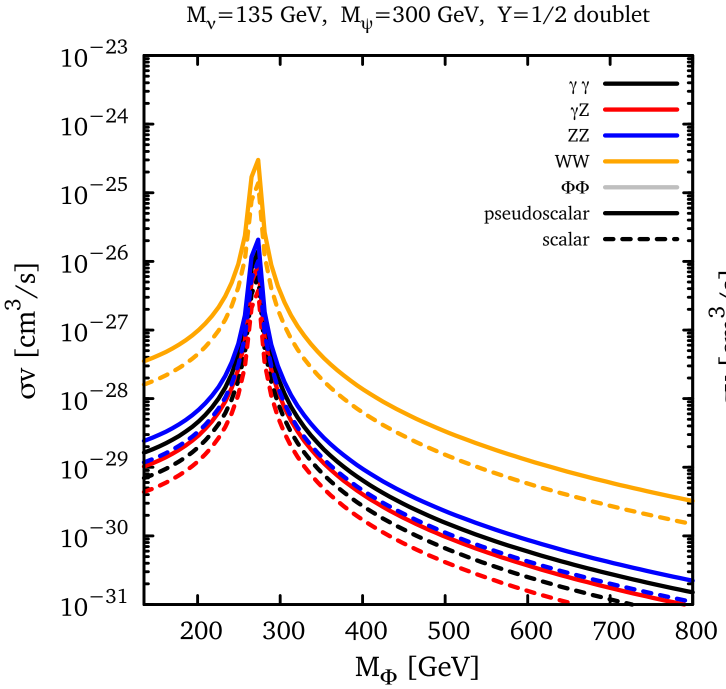
→ p-wave suppressed for scalar DM coupling

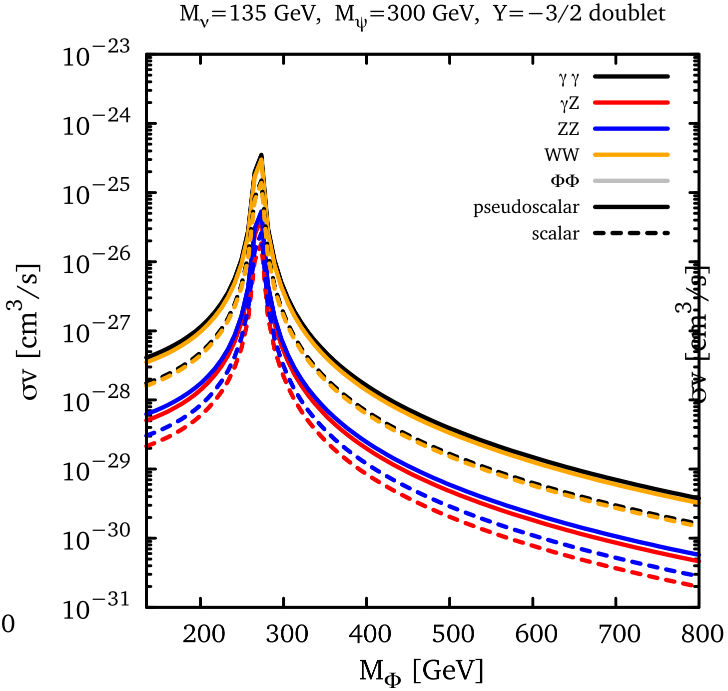
→ Concentrate on pseudo-scalar DM coupling

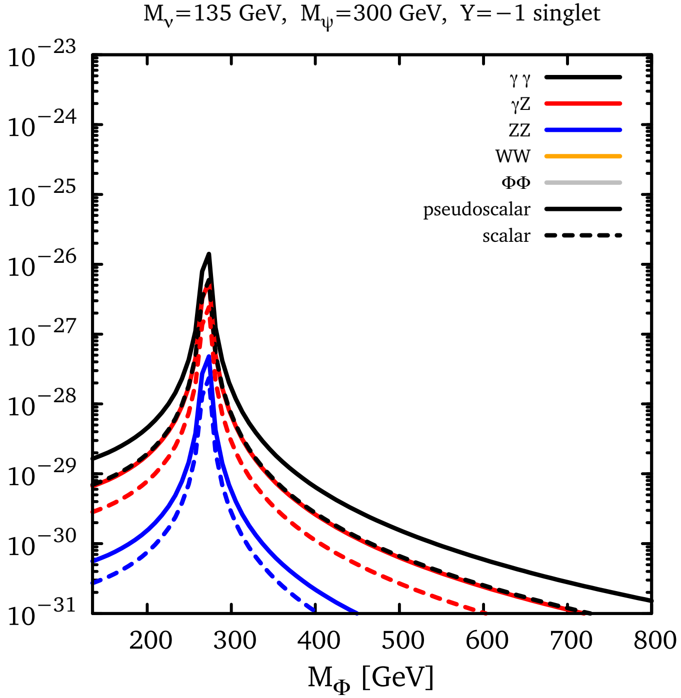
We consider different charge assignments for ψ .

$(SU(3),\, SU(2),\, U(1))$

- (1, 2, 1/2): $\psi_{1/2} = (\psi^+, \psi^0)$;
- (1, 2, -3/2): $\psi_{-3/2} = (\psi^-, \psi^{--})$;
- (1, 1, -1): $\psi_{-1} = \psi^-$.

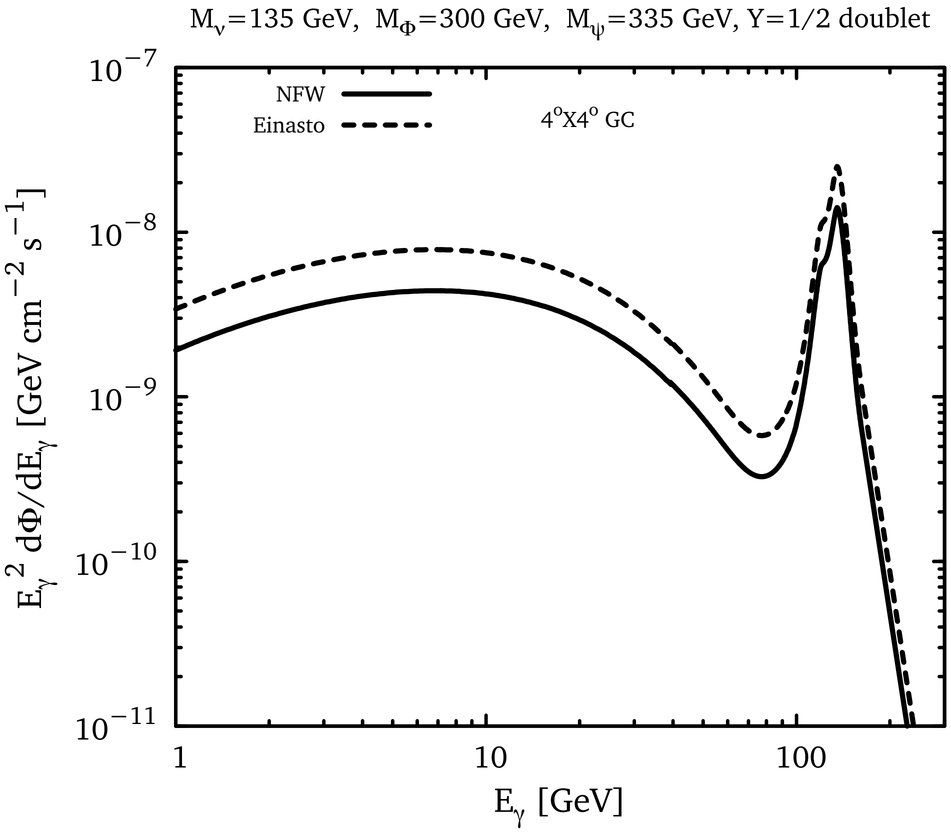


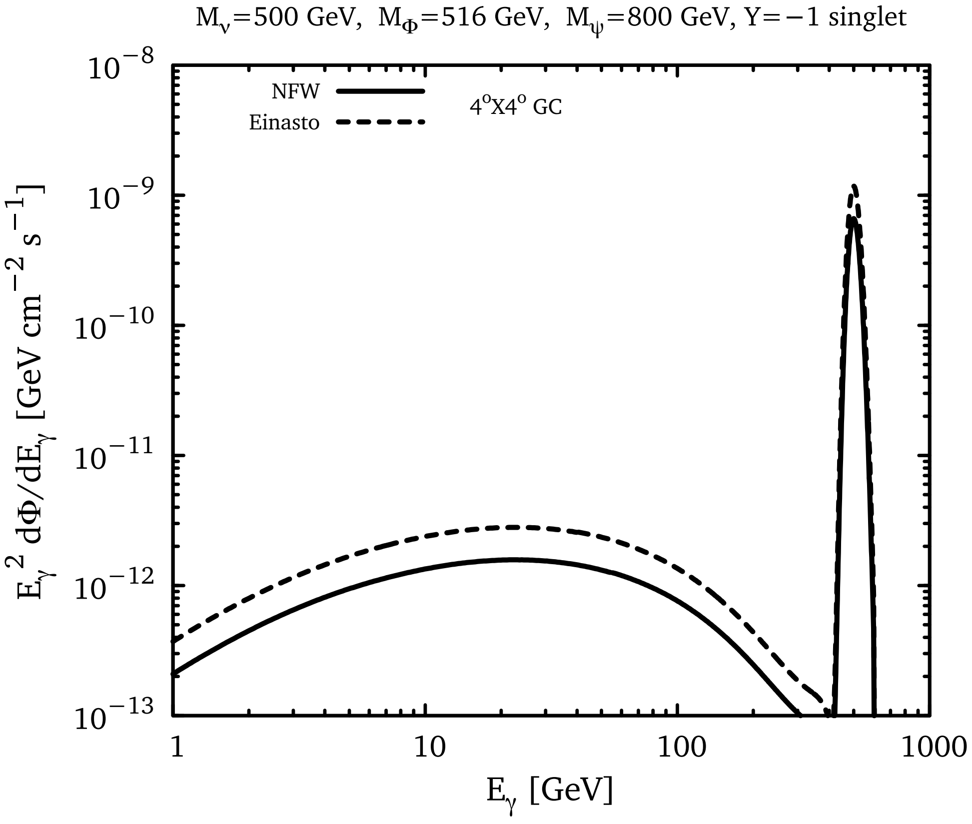




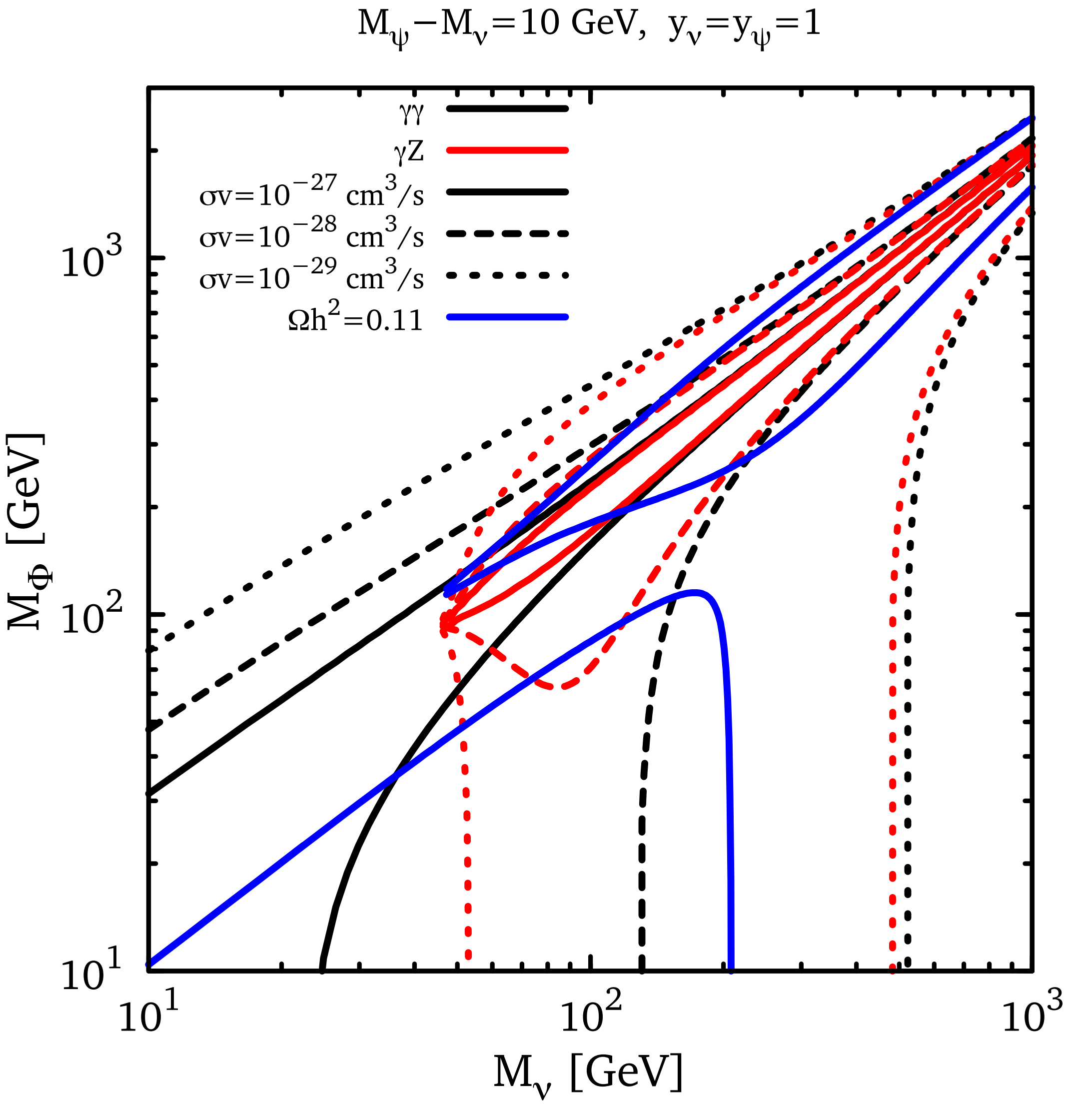
	ψ_{-1}	$\psi_{-3/2}$	$\psi_{1/2}$
$\sigma_{\gamma Z}/\sigma_{cont}$	10	0.5	0.02
$\sigma_{\gamma\gamma}/\sigma_{cont}$	30	1	0.04

Predicted gamma ray spectra


M_ν=135 GeV, M_Φ=300 GeV, M_ψ=335 GeV, Y=1/2 doublet


M_ν=500 GeV, M_Φ=516 GeV, M_ψ=800 GeV, Y=−1 singlet

Strength of gamma ray lines versus relic density



easy to get the correct relic abundance, either via Φ-h mixing or via $\nu\bar{\nu} \rightarrow \psi\bar{\psi}$

+ very weak constraints on mass of ψ

Summary of scalar case

pseudoscalar coupling of DM needed

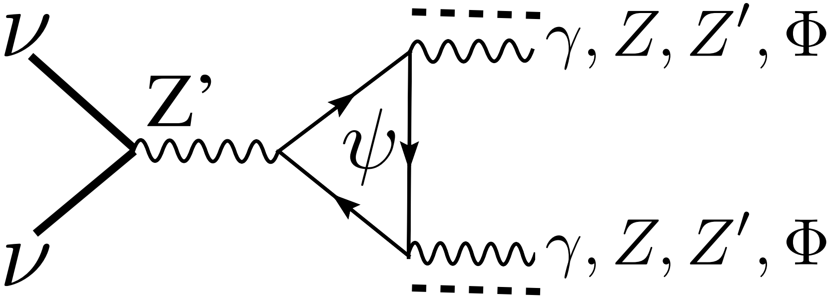
ZZ and WW continuum can be sizeable depending on the charge assignments of ψ.

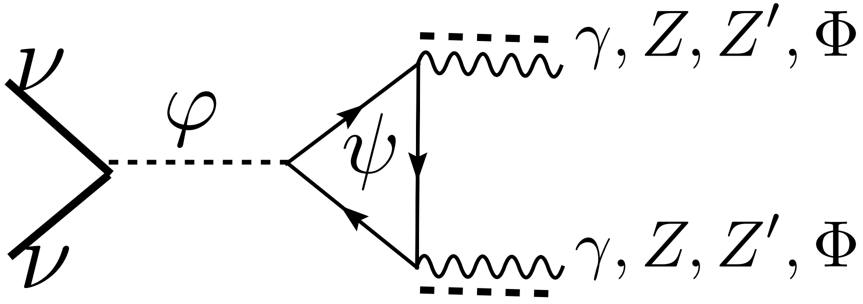
Case with vector mediator:

Extend SM gauge sector by adding a U(1)'
gauge symmetry broken by the vev of Φ

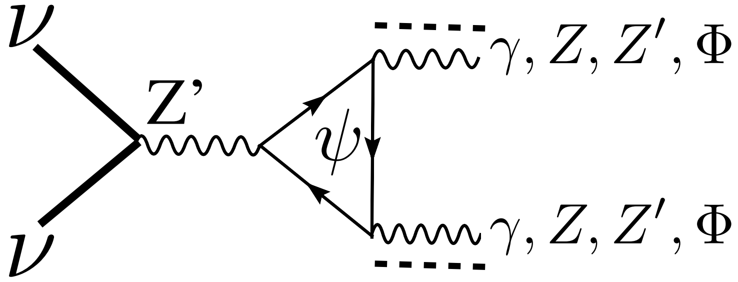
phenomenology very similar to previous scalar case

DM and ψ charged under U(1)'





One-loop cross sections are very sensitive to the vector or axial nature of the couplings



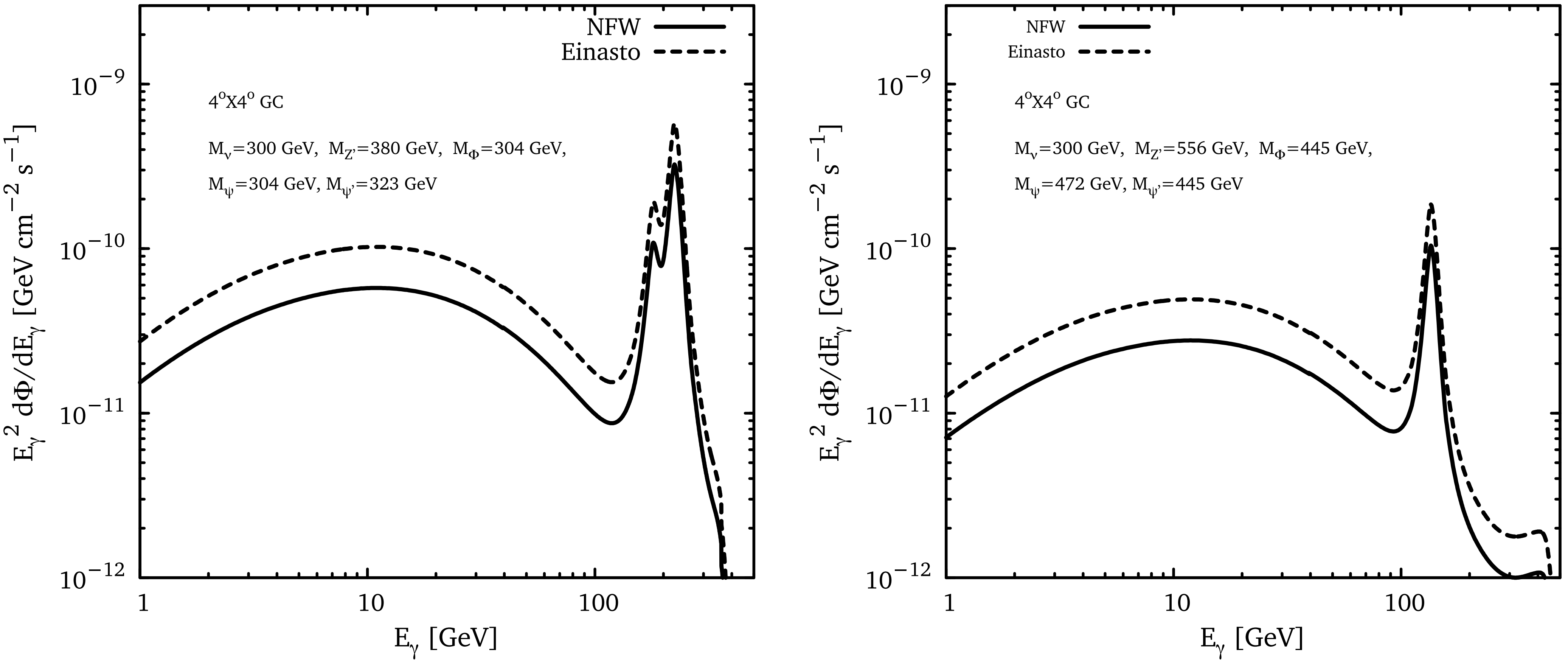
all one-loop cross sections vanish if all couplings in the loop are vector-like

$g_{\nu Z'} = g^V_{\nu Z'}$							$g_{\nu Z'} = g^A_{\nu Z'}$				$g_{\nu Z'} = g^V_{\nu Z'} + g^A_{\nu Z'}$		
$g_{\psi Z}$	V	V	V	A	V+A	V+A	V	V	V	V+A	V	V	V
$g_{\psi Z'}$	V	A	V+ A	V	V	V+A	V	A	V+A	V+A	V	A	V+A
$\gamma\gamma$	0	0	0	0	0	0	0	✓	✓	✓	0	✓	✓
γZ	0	✓	✓	✓	✓	✓	0	✓	✓	✓	0	✓	✓
$\gamma Z'$	0	0	✓	0	0	✓	0	0	✓	✓	0	0	✓
$\gamma\Phi$	0	0	✓	0	0	✓	0	0	0	0	0	0	✓
ZZ	0	✓	✓	0	✓	✓	0	✓	✓	✓	0	✓	✓
ZZ'	0	0	✓	✓	✓	✓	0	0	✓	✓	0	0	✓
$Z\Phi$	0	✓	✓	0	0	✓	0	✓	✓	✓	0	✓	✓
$Z'\Phi$	0	✓	✓	0	0	✓	0	0	✓	✓	0	✓	✓
$\Phi\Phi$	0	0	0	0	0	0	0	✓	✓	✓	0	✓	✓
$Z'Z'$	0	✓	✓	0	0	✓	0	✓	✓	✓	0	✓	✓

potentially multiple lines

$\gamma\gamma$ channel if DM and ψ both have axial couplings

Scalar in space !

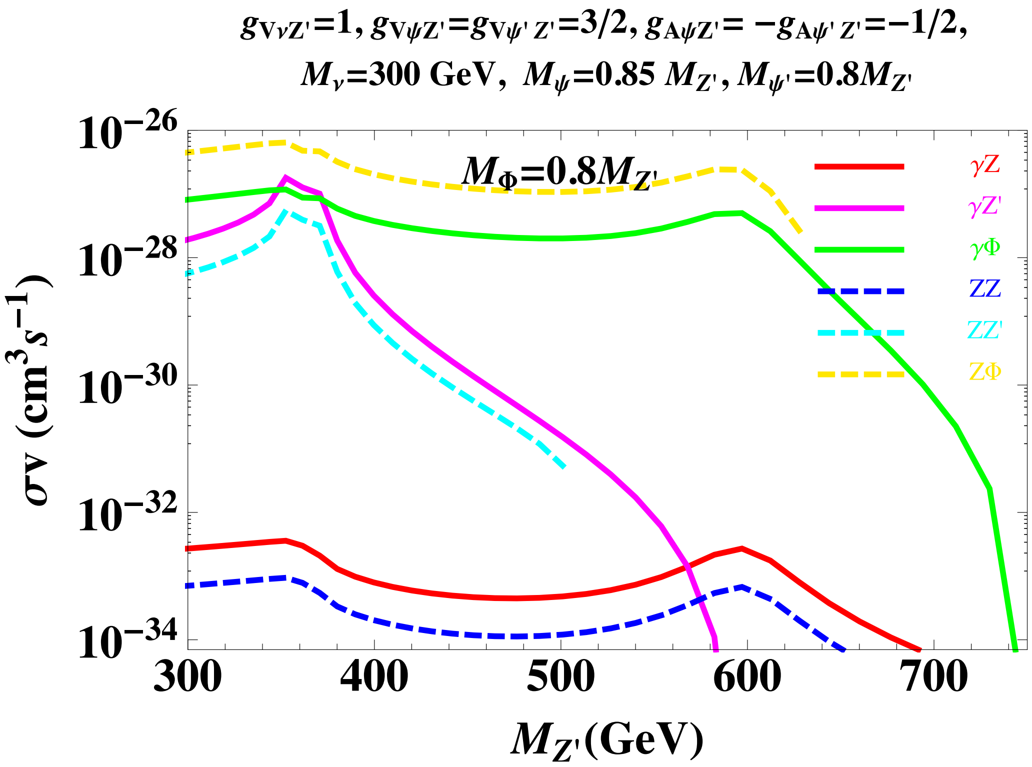


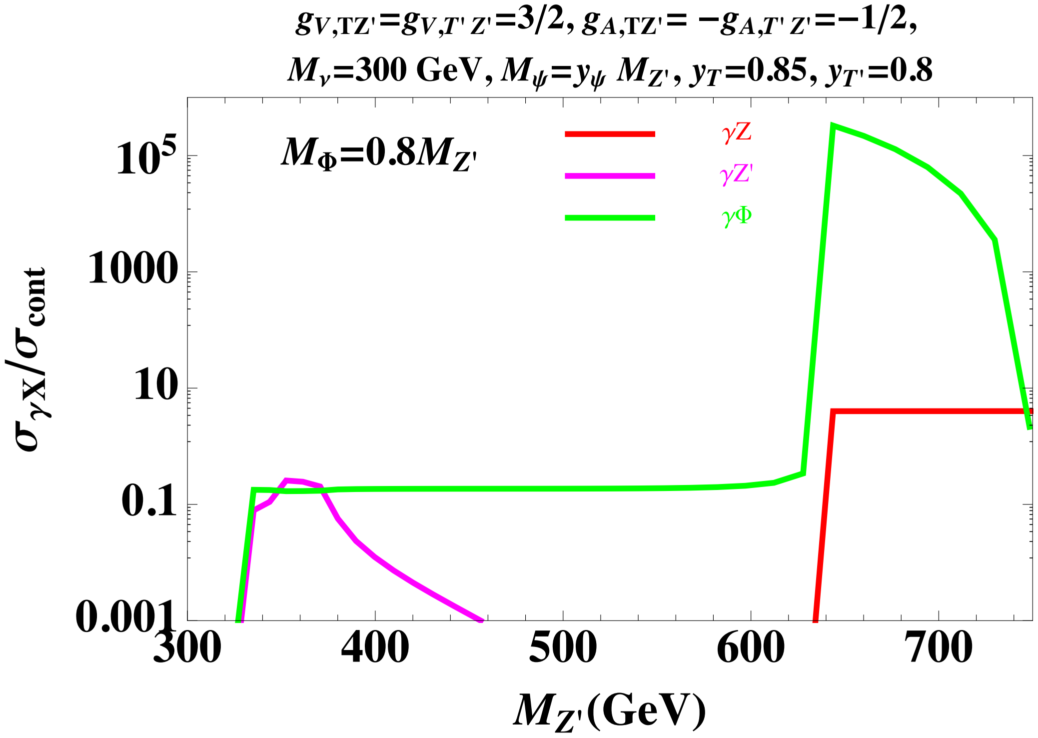
photon spectrum from DM annihilation in galactic center. Line due to $\gamma\Phi$ channel

(and $\gamma Z'$)

The $\gamma\Phi$ line typically dominates

γZ is relatively very suppressed

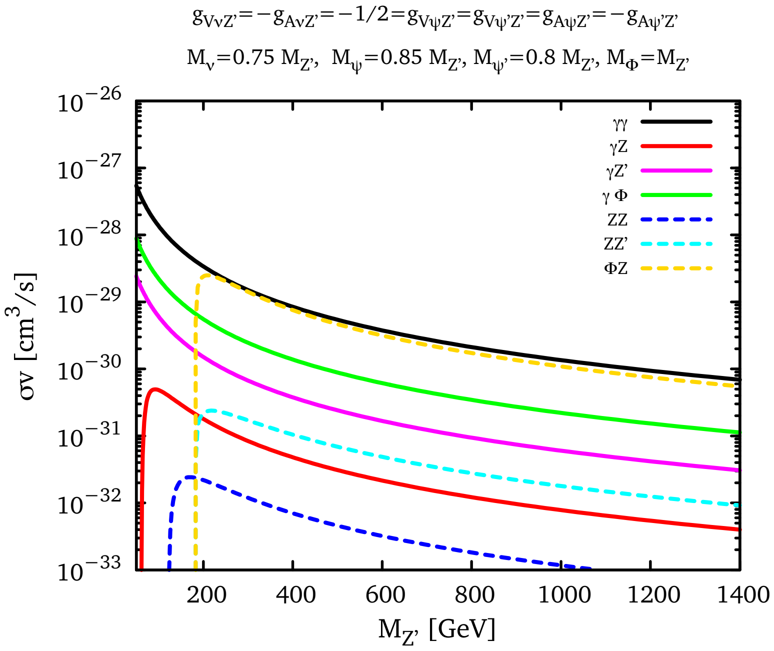

$g_{V\nu Z'}=1, g_{V\psi Z'}=g_{V\psi' Z'}=3/2, g_{A\psi Z'}=-g_{A\psi' Z'}=-1/2,$
$M_\nu=300$ GeV, $M_\psi=0.85\,M_{Z'}, M_{\psi'}=0.8M_{Z'}$


$g_{V,TZ'}=g_{V,T'Z'}=3/2, g_{A,TZ'}=-g_{A,T'Z'}=-1/2,$
$M_\nu=300$ GeV, $M_\psi=y_\psi\,M_{Z'}, y_T=0.85, y_{T'}=0.8$

$Z\Phi$ is the dominant (but mild) continuum

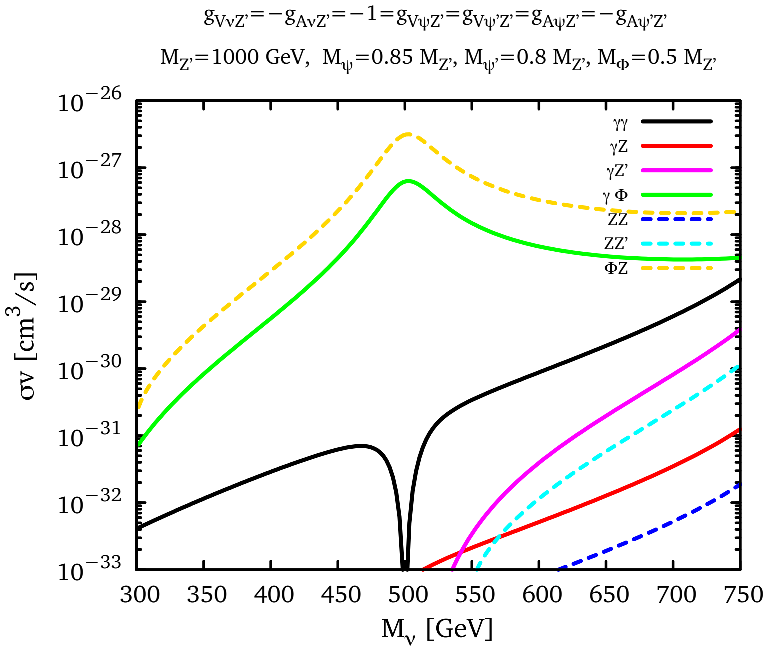
This is a case where DM has vector-like couplings.

Case where DM has axial-vector couplings.



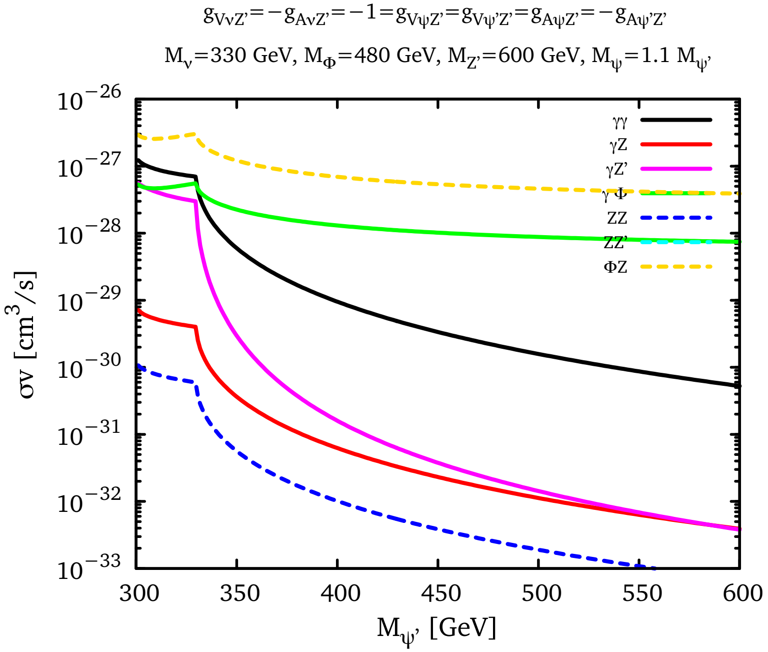
$g_{V\nu Z'}=-g_{A\nu Z'}=-1/2=g_{V\psi Z'}=g_{V\psi' Z'}=g_{A\psi Z'}=-g_{A\psi' Z'}$

$M_\nu=0.75\ M_{Z'}$, $M_\psi=0.85\ M_{Z'}$, $M_{\psi'}=0.8\ M_{Z'}$, $M_\Phi=M_{Z'}$



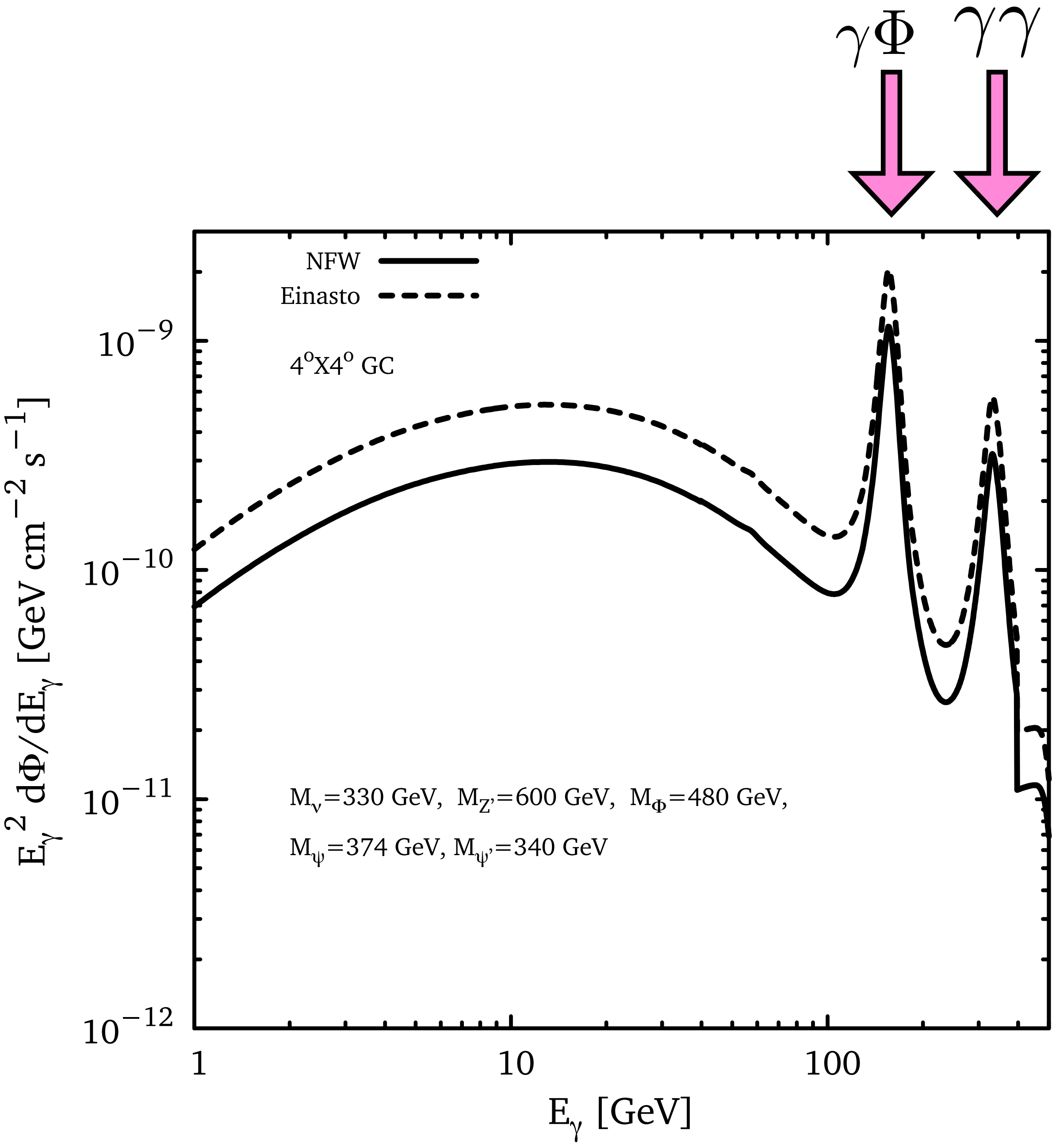
$g_{V\nu Z'}=-g_{A\nu Z'}=-1=g_{V\psi Z'}=g_{V\psi' Z'}=g_{A\psi Z'}=-g_{A\psi' Z'}$

$M_{Z'}=1000$ GeV, $M_\psi=0.85\ M_{Z'}$, $M_{\psi'}=0.8\ M_{Z'}$, $M_\Phi=0.5\ M_{Z'}$



$g_{V\nu Z'}=-g_{A\nu Z'}=-1=g_{V\psi Z'}=g_{V\psi' Z'}=g_{A\psi Z'}=-g_{A\psi' Z'}$

$M_\nu=330$ GeV, $M_\Phi=480$ GeV, $M_{Z'}=600$ GeV, $M_\psi=1.1\ M_{\psi'}$


γΦ
γγ
NFW
Einasto
4°X4° GC
M_ν=330 GeV, M_Z'=600 GeV, M_Φ=480 GeV,
M_ψ=374 GeV, M_ψ'=340 GeV
10^−9
10^−10
10^−11
10^−12
1
10
100
E_γ^2 dΦ/dE_γ [GeV cm^−2 s^−1]
E_γ [GeV]

A purely vector-like model

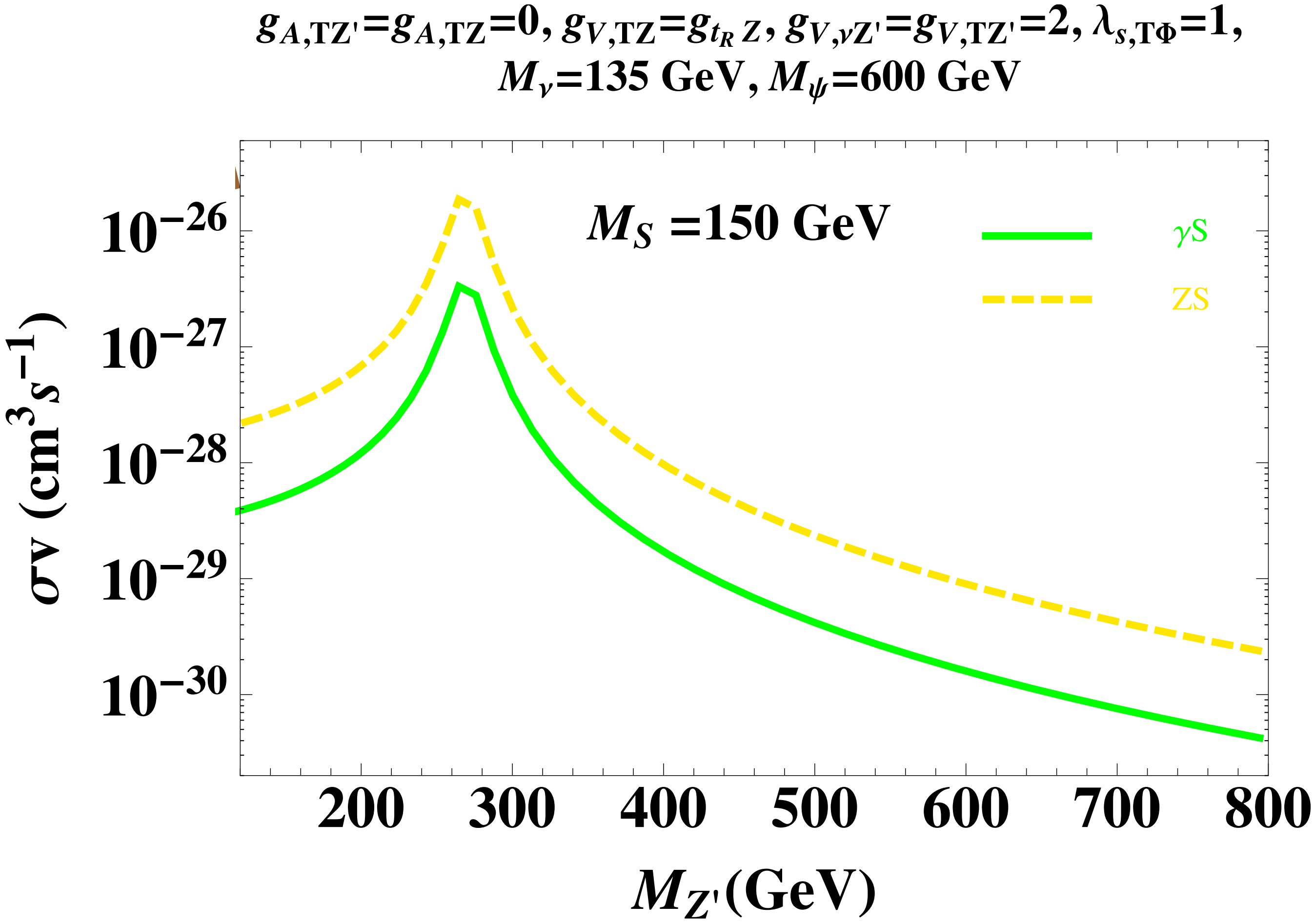
Signals from a scalar singlet S !

For instance well-motivated in composite Higgs models based on SO(6)->SO(5)

Strong gamma-ray line from the γS channel mediated by Z'

	λ_ν: scalar		λ_ν: pseudoscalar	
λ_ψ	scalar	pseudoscalar	scalar	pseudoscalar
$\gamma\gamma$	0	0	✓	✓
γZ	0	0	✓	✓
$\gamma Z'$	0	0	✓	✓
γS	✓	✓	✓	✓
ZZ	0	0	✓	✓
ZZ'	0	0	✓	✓
ZS	✓	0	✓	0
$Z'S$	✓	0	✓	0
SS	✓	0	✓	0
$Z'Z'$	0	0	✓	✓

almost no continuum.


$g_{A,TZ'}=g_{A,TZ}=0, g_{V,TZ}=g_{t_R Z}, g_{V,\nu Z'}=g_{V,TZ'}=2, \lambda_{s,T\Phi}=1,$
M_ν=135 GeV, M_ψ=600 GeV
M_S =150 GeV
γS
ZS
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
σv (cm$^3 s^{-1}$)
200
300
400
500
600
700
800
$M_{Z'}$(GeV)

Summary

Both scalar and vector resonance models can lead to large line signals as well as large line/continuum ratios

s-channel vector mediators require chiral couplings to the fermion running in the loop whereas scalar mediators require pseudo scalar coupling to DM.

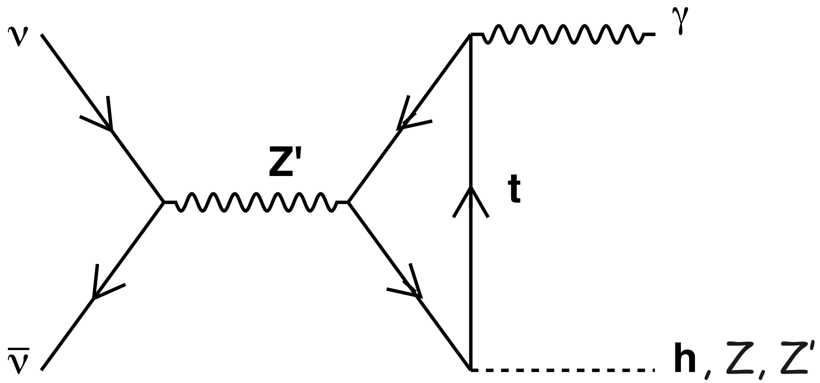
In the cases considered so far, we assumed that the new fermions ψ have negligible mixing with SM fermions

Next step: introduce mixing ...

The Dark Matter-SM connection via mass mixing

The top quark portal

0912.0004
1303.4717



simple UV completion

$$yH\bar{\hat{Q}}_3\hat{t}_R + \mu\bar{\psi}_L\psi_R + Y\Phi\bar{\psi}_L\hat{t}_R$$

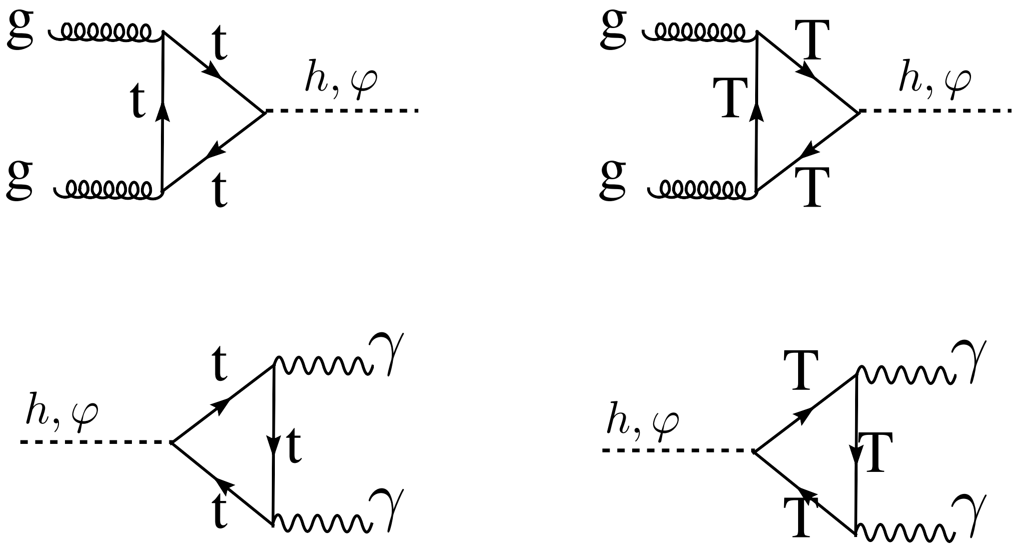
mass
eigen
states

$$\begin{pmatrix} t_{R/L} \\ T_{R/L} \end{pmatrix} = \begin{pmatrix} -\sin\theta_{R/L} & \cos\theta_{R/L} \\ \cos\theta_{R/L} & \sin\theta_{R/L} \end{pmatrix} \begin{pmatrix} \hat{t}_{R/L} \\ \Psi_{R/L} \end{pmatrix} \qquad M_T = m_t\,\frac{\tan\theta_L}{\tan\theta_R}$$

$$\tan\theta_R = \frac{\mu^2 - y^2\langle H^2\rangle - Y^2\langle\Phi^2\rangle + \sqrt{-4\mu^2y^2\langle H^2\rangle + (\mu^2 + y^2\langle H^2\rangle + Y^2\langle\Phi^2\rangle)^2}}{2\mu Y\langle\Phi\rangle}$$

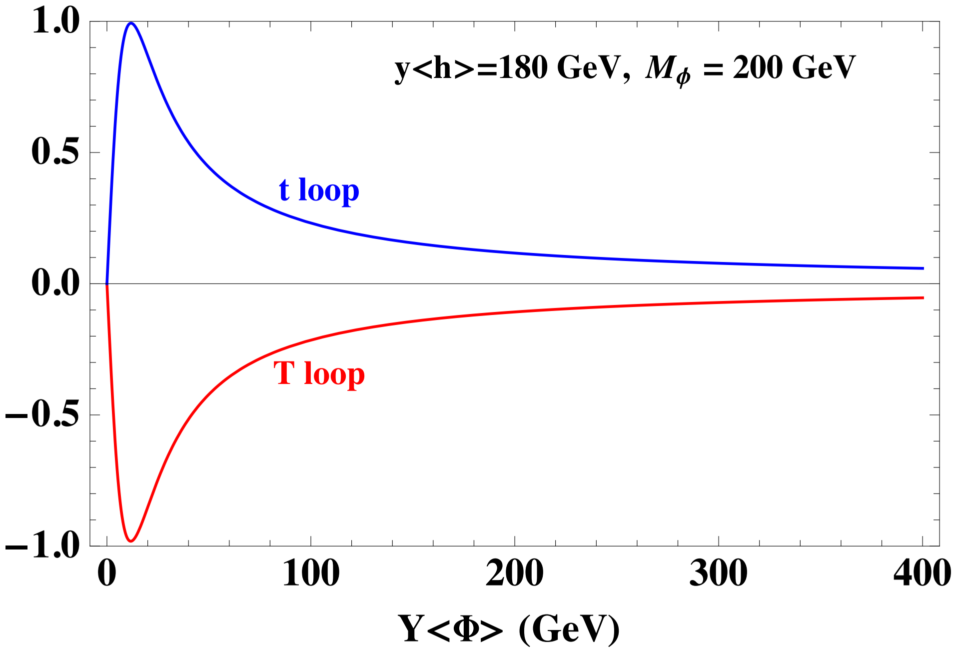
$$\tan\theta_L = \frac{\mu^2 - y^2\langle H^2\rangle + Y^2\langle\Phi^2\rangle + \sqrt{-4\mu^2y^2\langle H^2\rangle + (\mu^2 + y^2\langle H^2\rangle + Y^2\langle\Phi^2\rangle)^2}}{2y\langle H\rangle Y\langle\Phi\rangle}$$

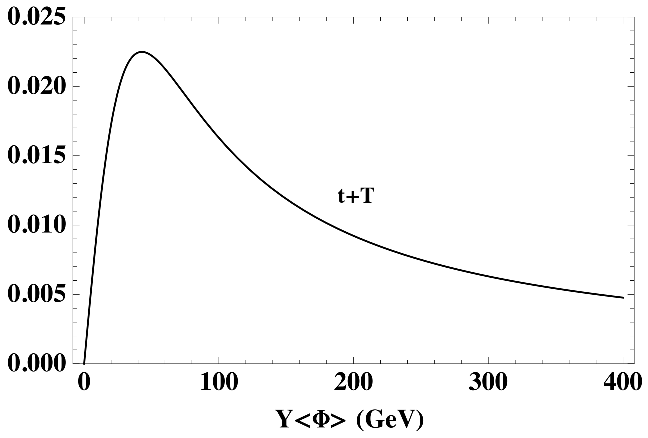
Higgs Physics



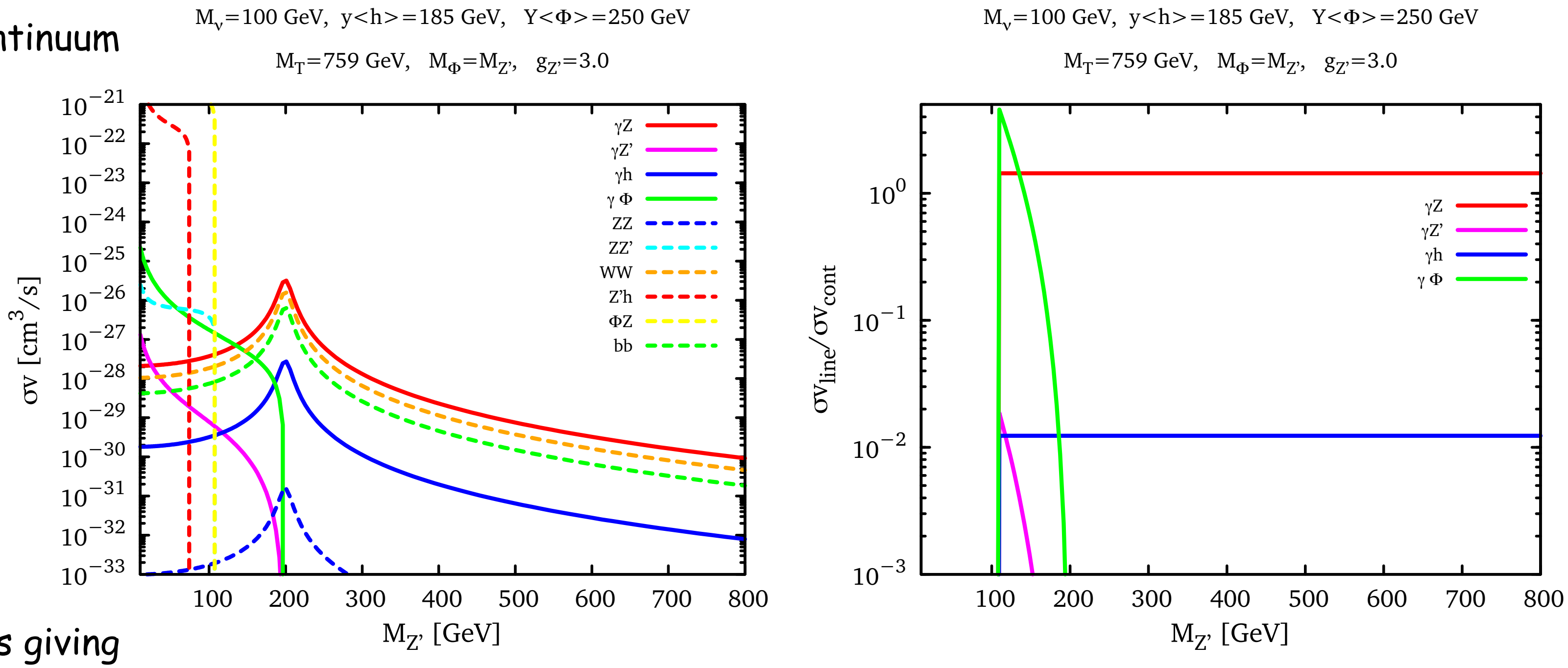
almost cancellation of new physics effects

$$\Gamma_{\phi\to gg} \propto \left| \frac{-c_L s_R F_{1/2}(\tau_t)}{m_t/v} + \frac{s_L c_R F_{1/2}(\tau_T)}{M_T/v} \right|^2$$

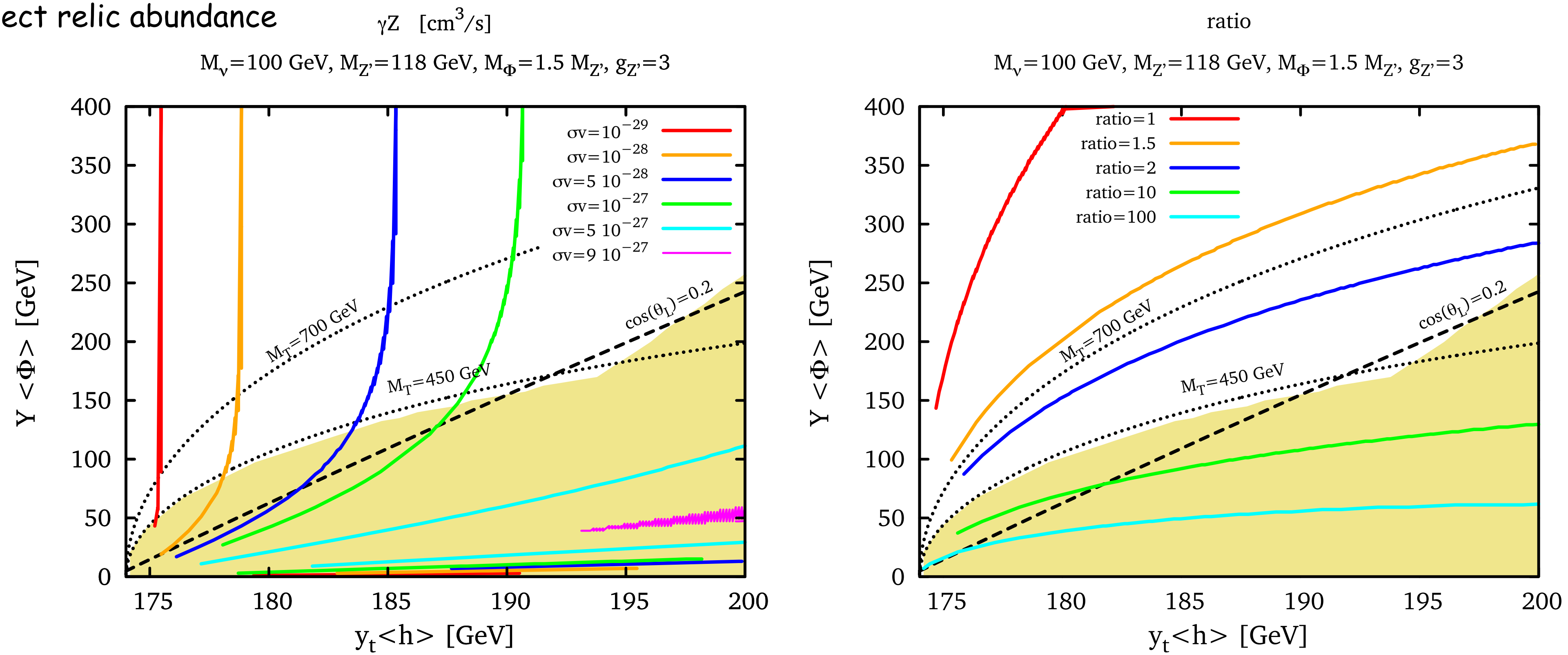


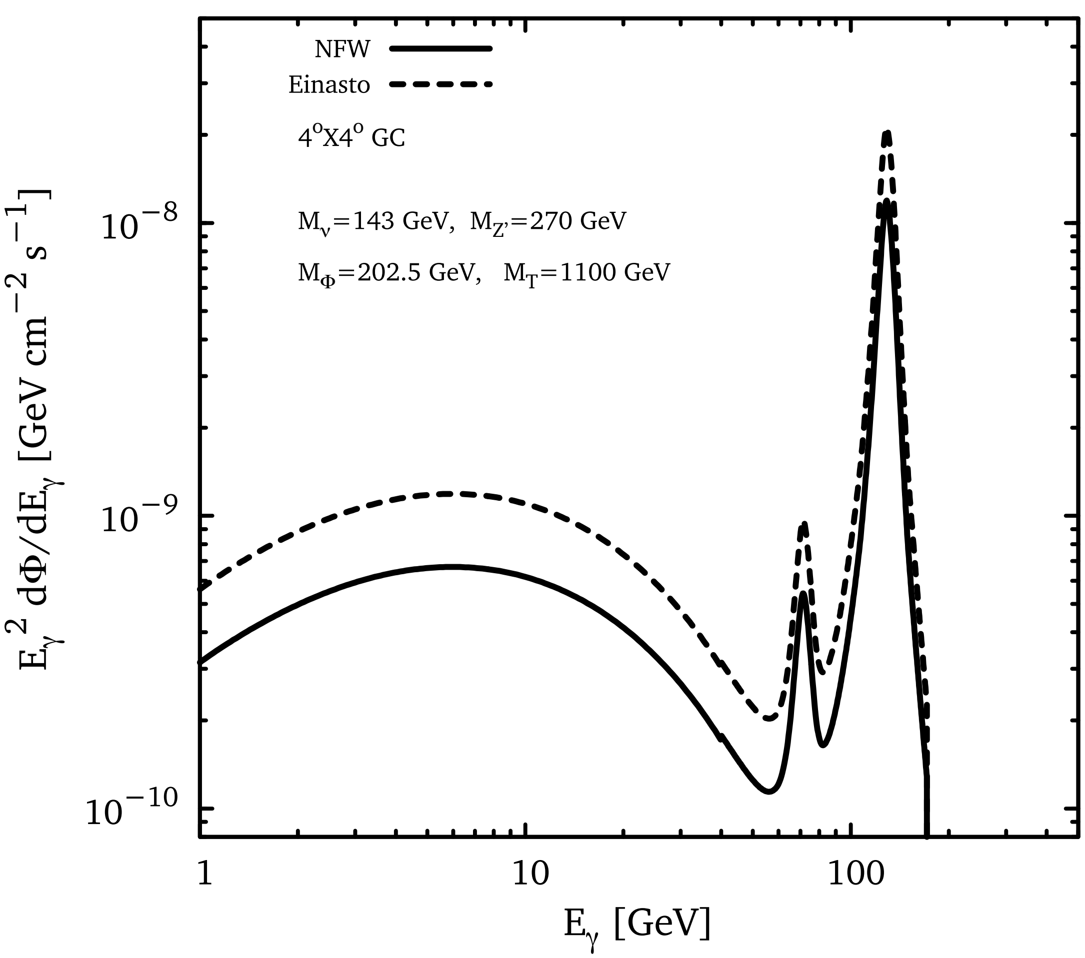


large line/continuum ratio

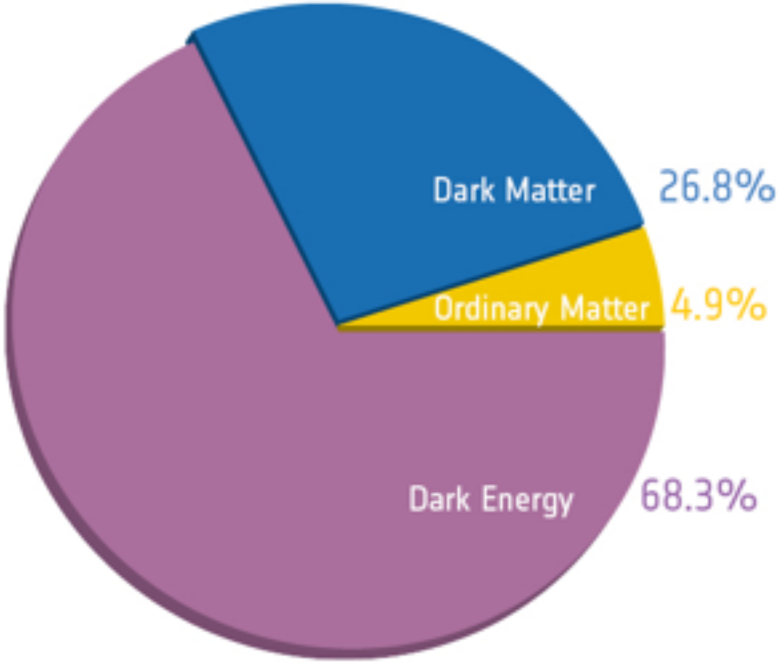


parameters giving correct relic abundance




NFW
Einasto
4°X4° GC
M_ν=143 GeV, $M_{Z'}$=270 GeV
M_Φ=202.5 GeV, M_T=1100 GeV
$E_\gamma^2\, d\Phi/dE_\gamma$ [GeV cm^{-2} s^{-1}]
10^{-8}
10^{-9}
10^{-10}
1
10
100
E_γ [GeV]

Are the Dark Matter and baryon abundances related ?



$\Omega_{DM} \approx 5\ \Omega_{baryons}$

Matter Anti-matter asymmetry of the universe:

characterized in terms of the
baryon to photon ratio

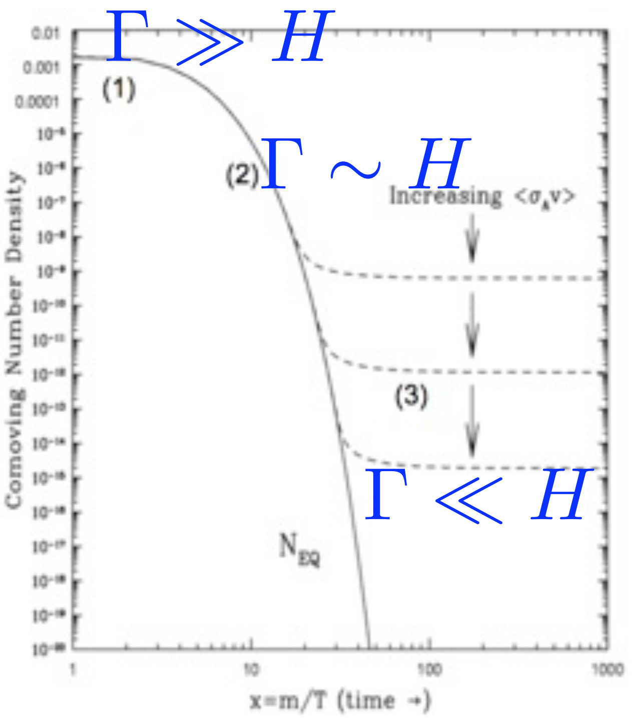
$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

~ 6. 10^{-10}

The great annihilation between
nucleons & anti-nucleons

$$n + \bar{n} \to \pi + \pi \to \gamma + \gamma + \ldots$$

occurs when $\Gamma \sim (m_N T)^{3/2} e^{-m_N/T}/m_\pi^2 \sim H \sim \sqrt{g_*} T^2/m_{Pl}$



corresponding to a freeze-out temperature T_F ~ 20 MeV

In absence of
an asymmetry:

$$\frac{n_N}{s} \approx 7 \times 10^{-20}$$

10^9 times smaller than observed,
and there are no antibaryons
-> need to invoke an initial asymmetry

10 000 000 001
Matter

10 000 000 000
Anti-matter

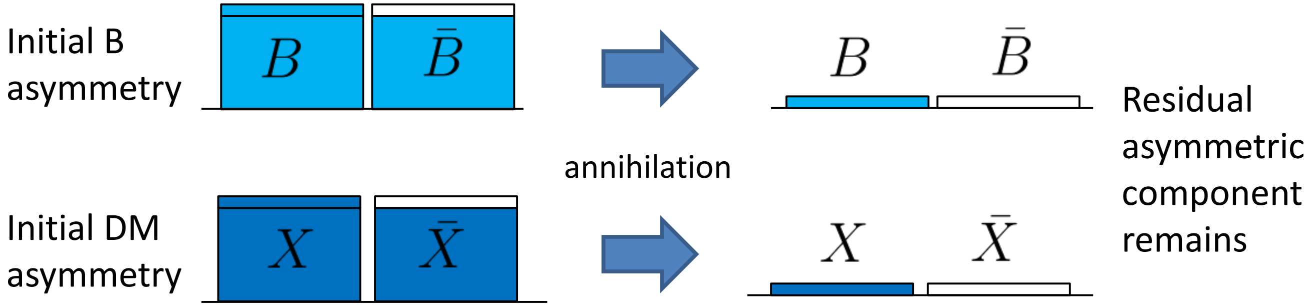
1
(us)

Similarly, Dark Matter may be asymmetric

$$\frac{\Omega_{dm}}{\Omega_b} \sim 5$$

Does this indicate a common dynamics?

If $n_{dm} - \overline{n}_{dm} \propto n_b - \overline{n}_b$



Initial B asymmetry

Initial DM asymmetry

annihilation

Residual asymmetric component remains

conservation of global charge:

$$Q_{\rm DM}(n_{\overline{\rm DM}} - n_{\rm DM}) = Q_b(n_b - n_{\bar{b}})$$

if efficient annihilations:

$$\frac{\Omega_{dm}}{\Omega_b} \sim \frac{Q_b}{Q_{dm}} \frac{m_{dm}}{m_b} \longrightarrow$$

typical expected mass ~ GeV

two possibilities:

1) asymmetries in baryons and in DM generated simultaneously

2) a pre-existing asymmetry (either in DM or in baryons) is transferred between the two sectors

Crucial role played by the Higgs in the 2 major theories of baryogenesis

- in EW baryogenesis: Higgs bubbles provide out-of-equilibrium dynamics

- in leptogenesis: Decay into the Higgs of RH neutrinos produce lepton asymmetry

New proposal

Servant & Tulin, PRL 111, 151601 (2013)

-The Higgs is playing a central role in connecting the baryonic matter generation to that of dark matter.
This offers new opportunities for baryogenesis and dark matter generation.

In particular, we present a mechanism of baryogenesis that does not rely any new sources of B or L violation beyond the Standard Model.

Starting observation:

In the early universe, at T>~ 100 GeV, before the EW phase transition, the thermal bath contains both Higgs particles and anti-Higgs particles since (since the Higgs doublet is a complex scalar)

We can therefore define an asymmetry between H and H*, particles and anti-particles of the Higgs field, like we do for leptons and quarks.

Standard Model equations describing chemical equilibrium in the hot plasma relate chemical potentials of the different species :

EW Sphalerons convert asymmetries between baryon and lepton number

$$\sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0$$

Yukawa interactions can induce a Higgs asymmetry

$$\begin{aligned} \mu_{q_i} - \mu_H - \mu_{d_j} &= 0 \ , \\ \mu_{q_i} + \mu_H - \mu_{u_j} &= 0 \ , \\ \mu_{\ell_i} - \mu_H - \mu_{e_j} &= 0 \ . \end{aligned}$$

Total hypercharge of the plasma

$$\sum_i (\mu_{q_i} + 2\mu_{u_i} - \mu_{d_i} - \mu_{\ell_i} - \mu_{e_i} + \frac{2}{N_f}\mu_H) = 0 \ .$$

⇨ a primordial asymmetry, say in leptons, induces a Higgs asymmetry though the equations of chemical equilibrium

Now assume that the Higgs couples to the dark sector. The previous equations will be modified such that the visible and dark asymmetries become related through the Higgs portal.

Note: Higgs asymmetry is rapidly erased after the EW phase transition since the Higgs vacuum expectation value violates Higgs number, as opposed to lepton number, which is frozen in.

In light of the recent Higgs discovery, it is tempting to ask under which circumstances the asymmetries produced in the early universe could have prevailed today and whether the Higgs asymmetry could have mediated the relic abundance of baryons or dark matter.

Case I: A primordial lepton asymmetry can lead to asymmetric dark matter

Case II: A primordial asymmetry in the dark matter can lead to baryogenesis

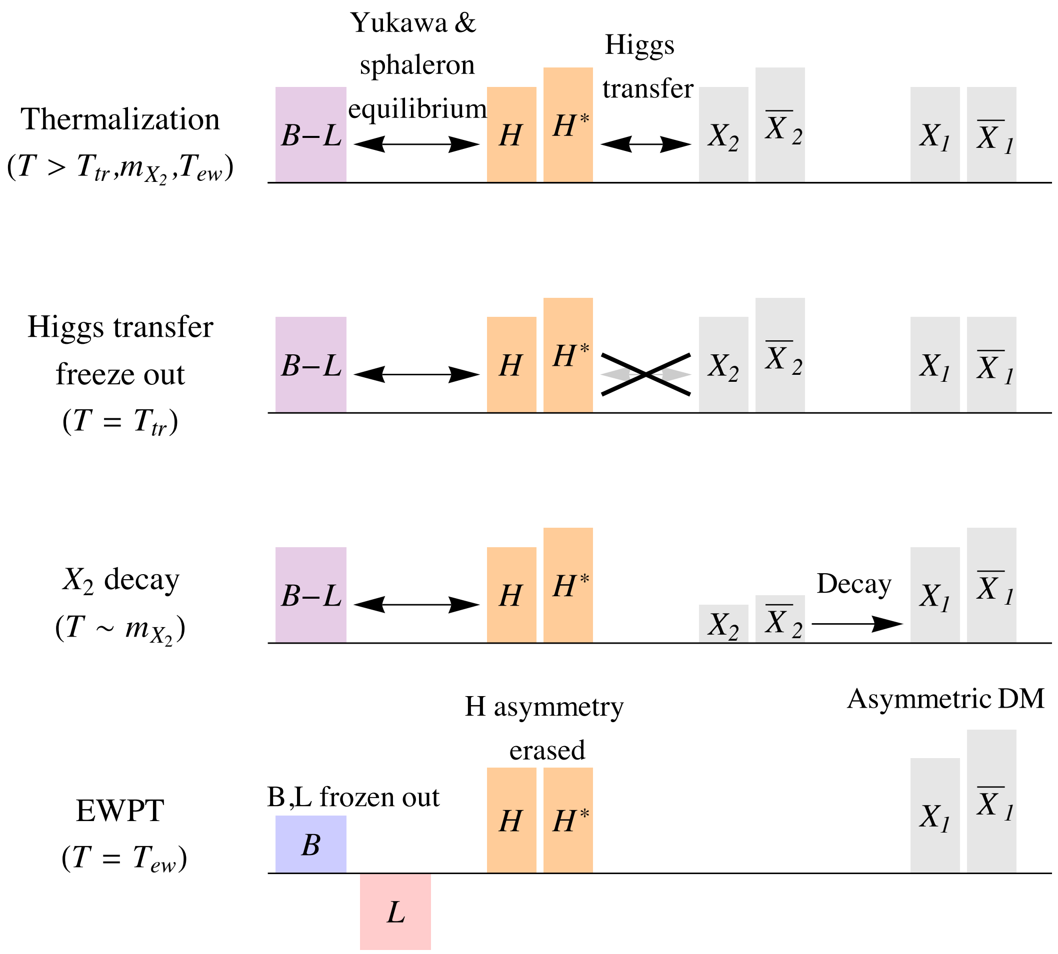
Minimal illustrative example

Just add to the Standard Model 2 vector-like fermions:
a singlet X_1 (Dark matter) and one EW doublet X_2 whose role is to transfer the asymmetries between the visible and dark sectors

$$\mathcal{L} \supset \frac{1}{\Lambda_2}(H^\dagger X_2)^2 + y_H \bar{X}_2 X_1 H + h.c$$

Case 1: Asymmetric Dark Matter from Lepto/Baryogenesis

Assume a primordial B-L asymmetry. It induces a Higgs asymmetry which flows into the dark sector



Thermalization ($T > T_{tr}, m_{X_2}, T_{ew}$)

Yukawa & sphaleron equilibrium

Higgs transfer

Higgs transfer freeze out ($T = T_{tr}$)

X_2 decay ($T \sim m_{X_2}$)

Decay

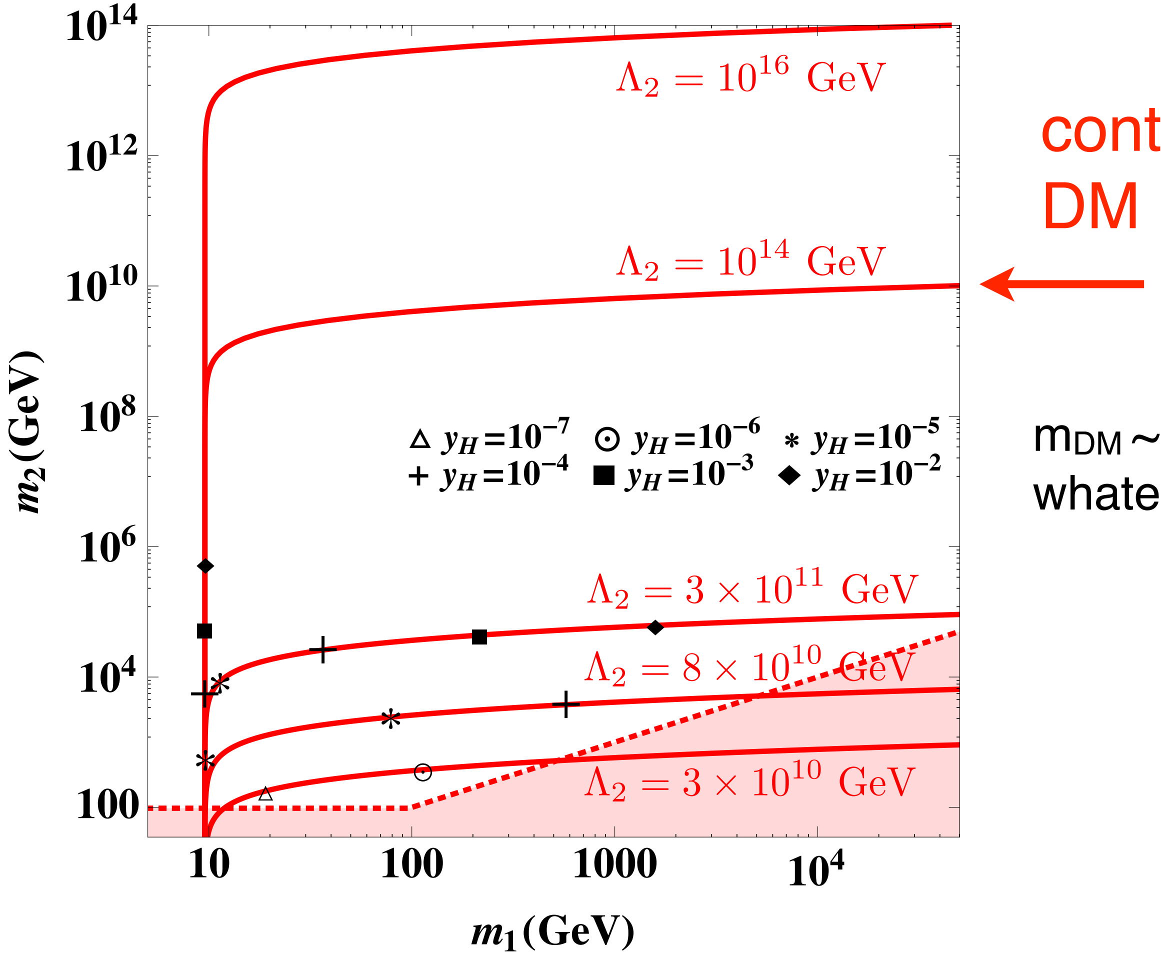
EWPT ($T = T_{ew}$)

B,L frozen out

H asymmetry erased

Asymmetric DM

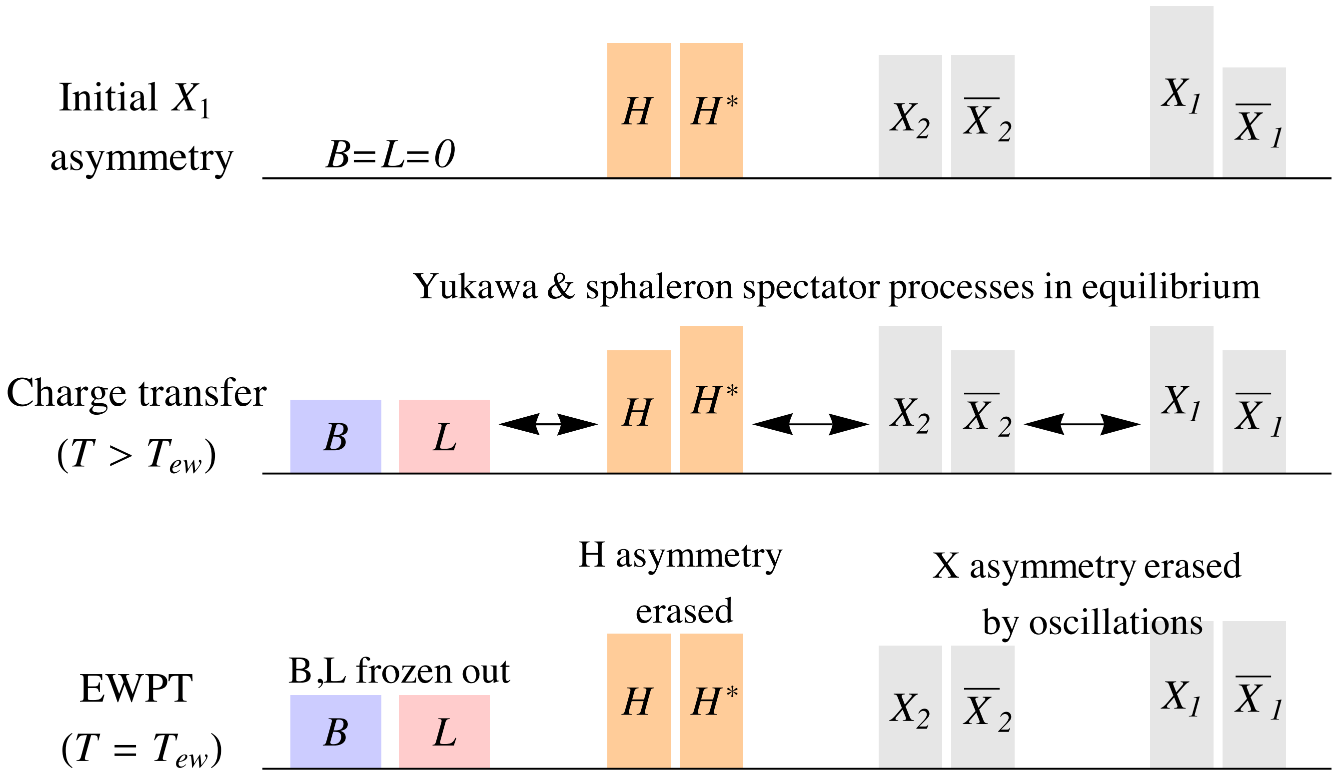
Such a scenario does not require new states that carry baryon or lepton number, unlike other Asymmetric DM models.



contours for correct DM relic abundance

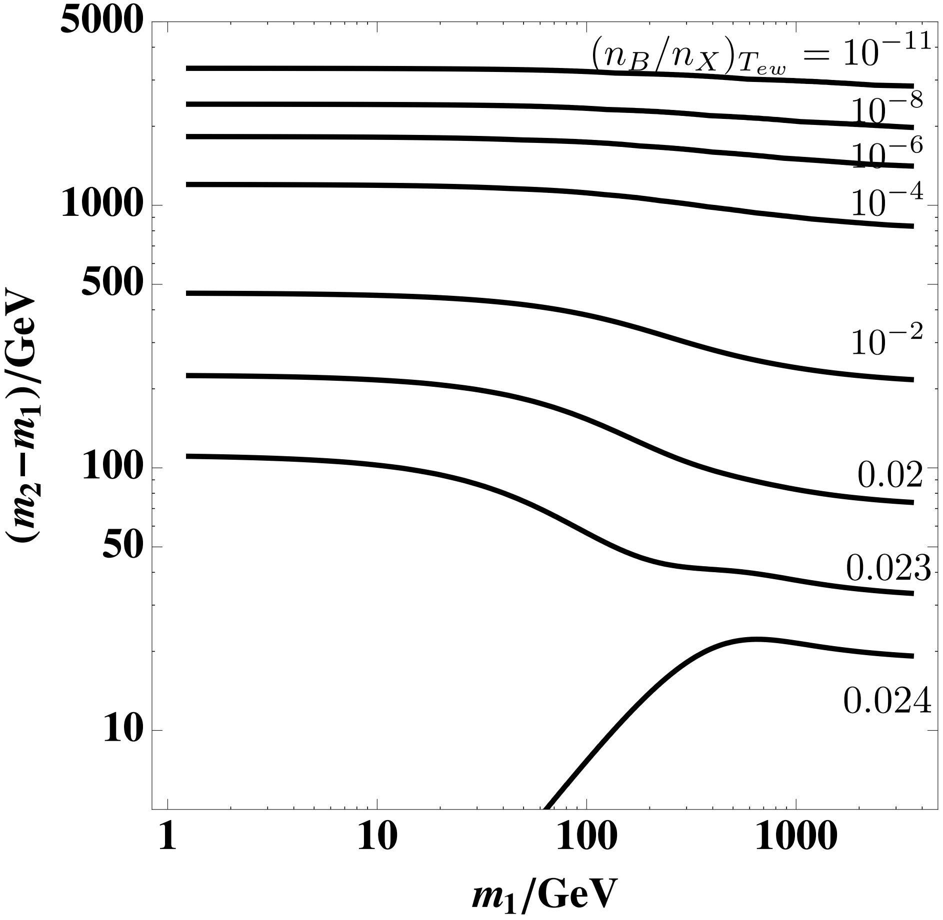
$m_{DM} \sim 10$ GeV is a generic prediction whatever the value of $\Lambda_2 \gtrsim 10^{10}$ GeV is.

Case 2: Baryogenesis from a primordial dark matter asymmetry



DM is no longer asymmetric today

A theory of baryogenesis that does not require B nor L violation beyond the SM but by having an asymmetry trapped in spectator X_2 we bias sphalerons into generating B+L.


$(n_B/n_X)_{T_{ew}} = 10^{-11}$
10^{-8}
10^{-6}
10^{-4}
10^{-2}
0.02
0.023
0.024
5000
1000
500
100
50
10
(m_2-m_1)/GeV
1
10
100
1000
m_1/GeV

Tests?

	Case 1	Case 2
indirect detection	✔	✔
direct detection	✔ only for heavy DM	✔
invisible higgs decay	✖	✔
LHC searches of X2	✔	✔

Effect of DM antiDM oscillations

Cirelli-Panci-Servant-Zaharijas '11

Rather generic is a small DM-number violating Majorana mass term , e.g.

$$\delta m \sim \phi^\dagger \phi / M_{pl}$$

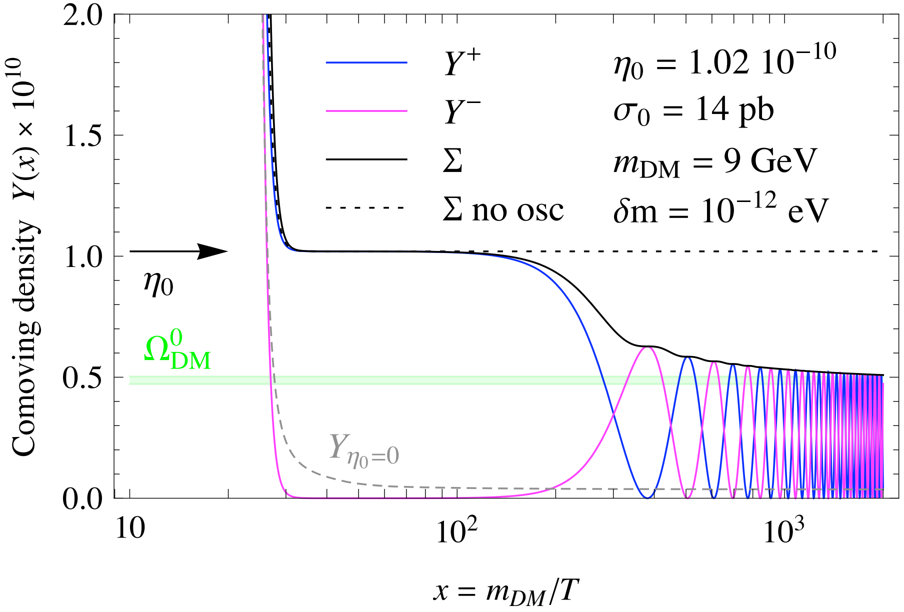
It introduces a splitting between X and X^c

and leads to oscillations between DM and antiDM when δ m ~ H~T^2/M_{Pl}

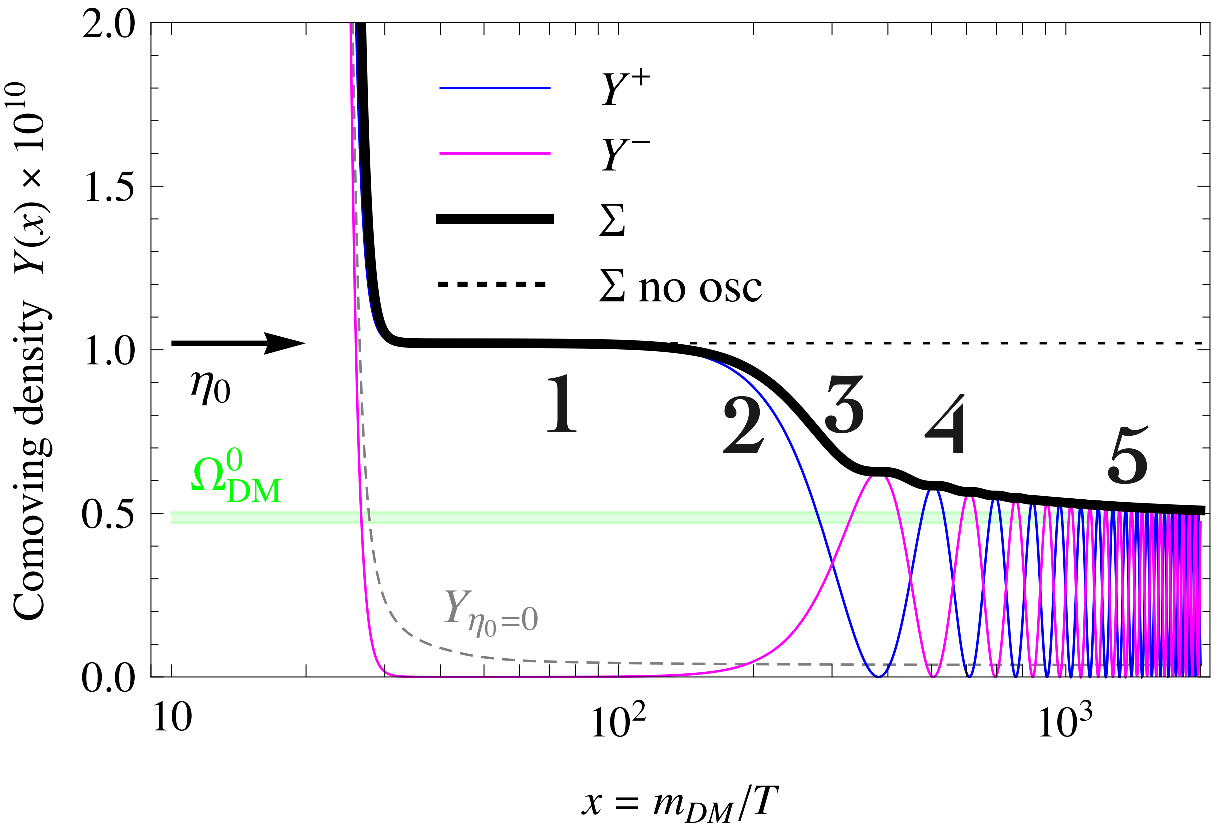
i.e. at T~ <ϕ> at EW scale!

re-equilibration of the initial
asymmetry before freese-out

re-establishment of annihilations



Asymmetric Dark Matter decoupling in presence of oscillations



1. Asymmetric 'freeze-out'
2. Oscillations repopulate Y^-
3. Annihilations recouple and lower the total DM density.
4. Process repeats in a series of plateaux.
5. Correct relic abundance can be achieved

η_0- primordial asymmetry.
Y^+/Y^- DM particle/antiparticle.
$\Sigma = Y^+ + Y^-$

$$\Omega_{DM} \to \Omega_{DM}\left(\langle\sigma v\rangle, \eta_0, m_{DM}, \delta m\right)$$

Scaling of WIMP relic abundance

- **symmetric DM:**

$$\Omega_{\rm DM} \propto \frac{1}{\sigma_0}$$

no explicit dependence on $m_{\rm DM}$

- **Asymmetric DM:**

$$\Omega_{\rm DM} \propto \frac{m_{\rm DM} \times \eta_0}{1 + A(\delta m^2 M_{Pl}^6 \sigma_0^4 \eta_0^4)^{1/5}}$$

$$\delta m \to 0$$

$$\Omega_{\rm DM} \propto m_{\rm DM} \times \eta_0$$

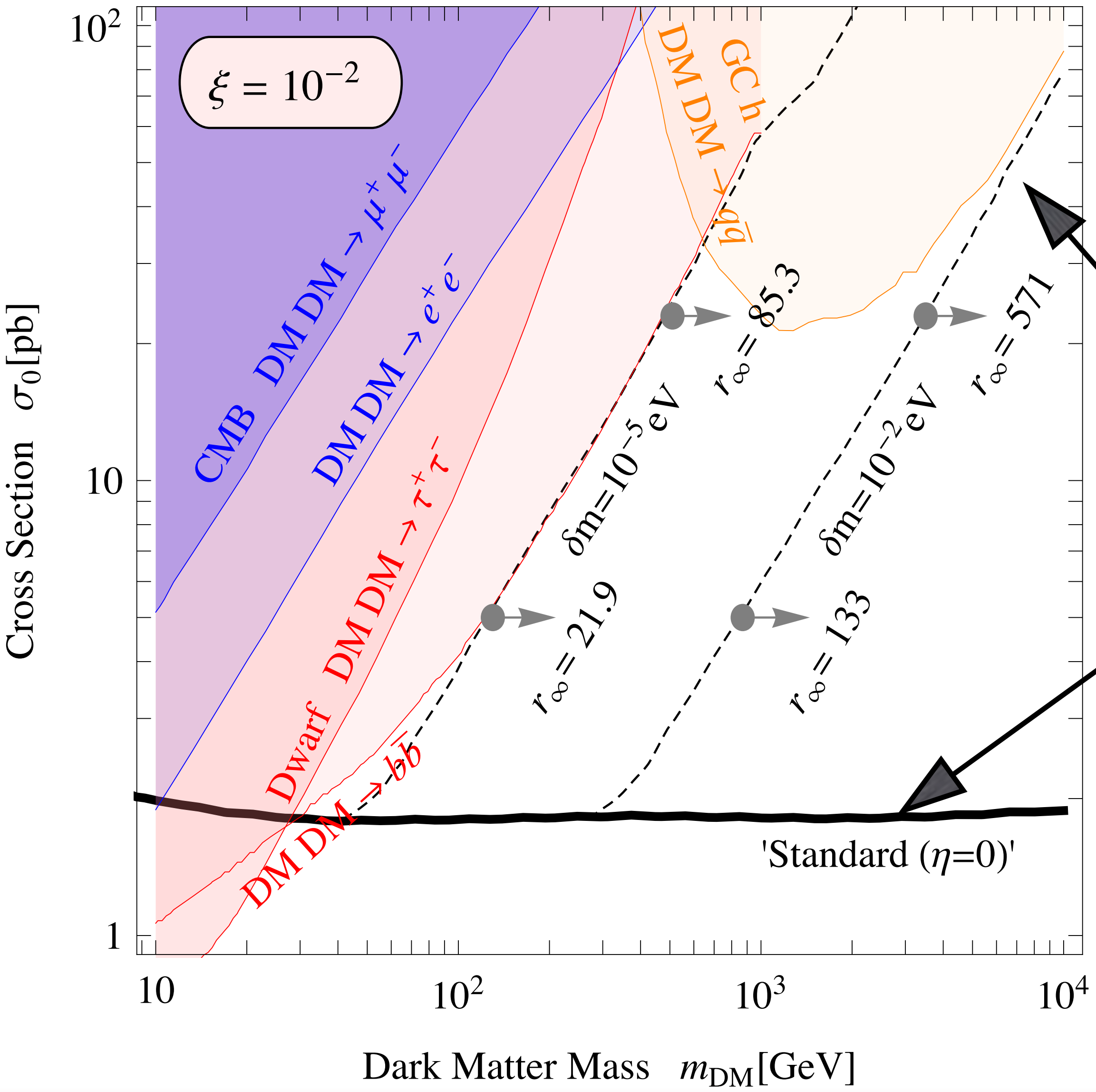
no dependence on σ_0

$$\delta m \gtrsim 1 \text{ eV}$$

$$\Omega_{\rm DM} \propto \frac{m_{\rm DM} \times \eta_0^{1/5}}{\delta m^{2/5} \sigma_0^{4/5}}$$

Explicit dependence on $m_{\rm DM}$

CMB versus Fermi constraints

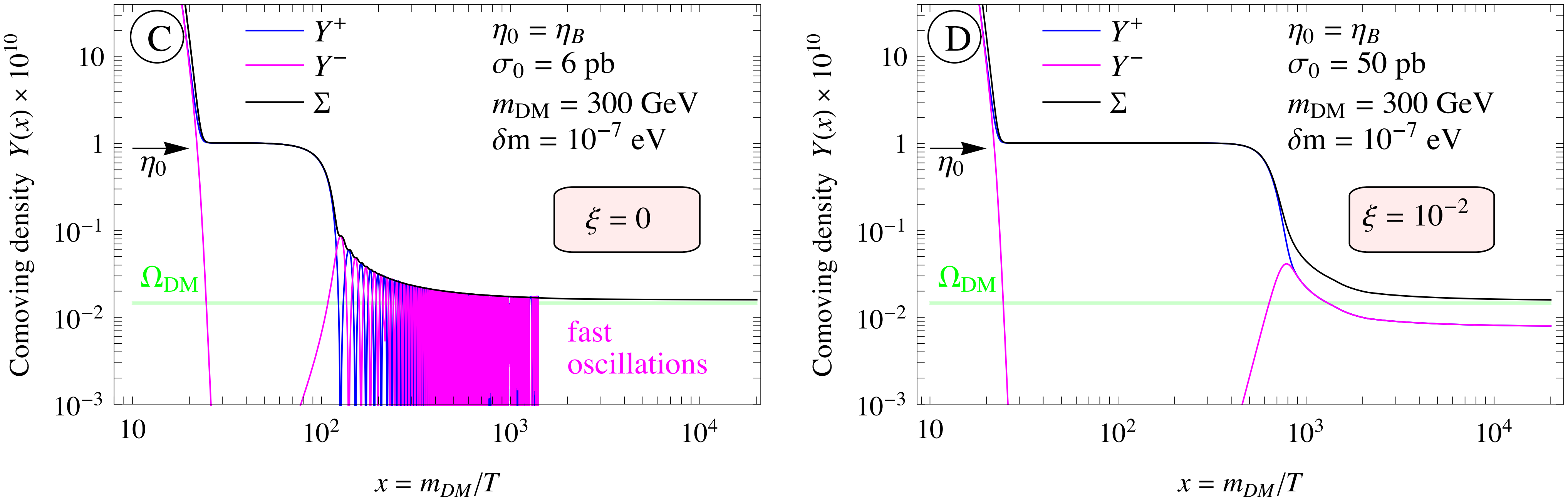


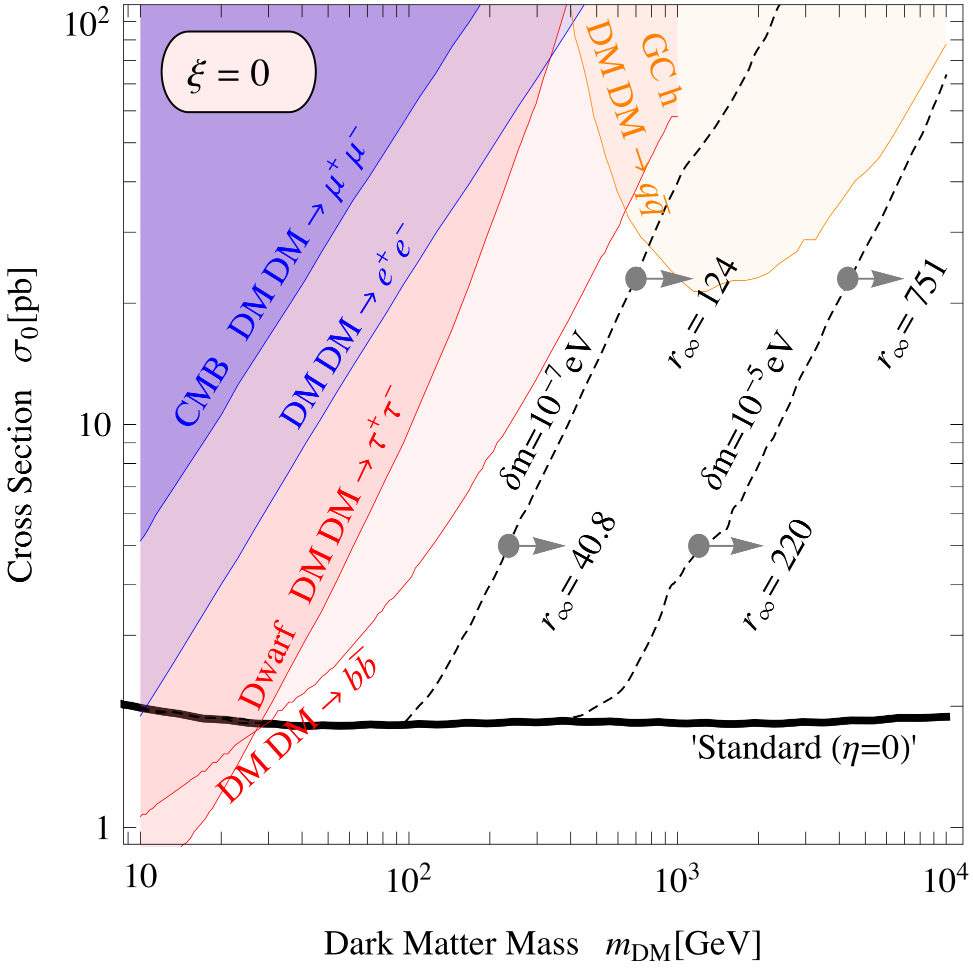
contours with correct
relic abundance

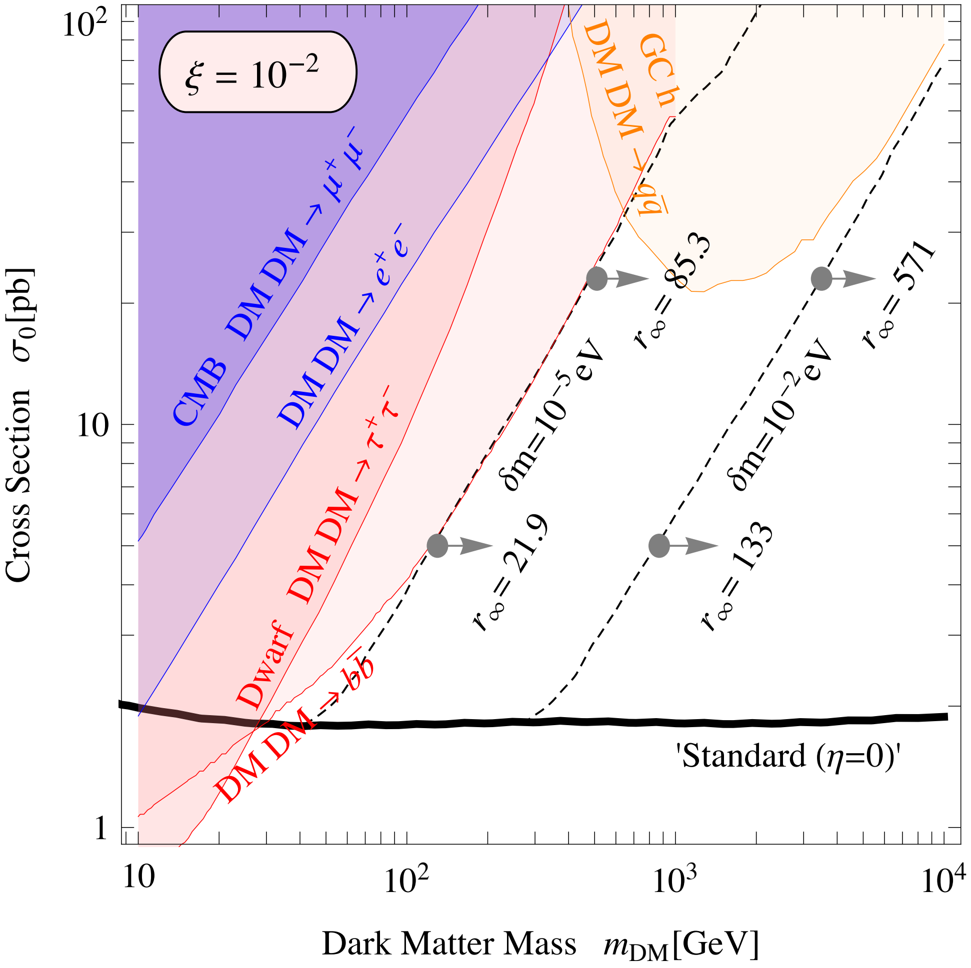
Large masses
allowed

DM oscillations are especially relevant for theories with DM-baryogenesis connection

DM scatterings delay the onset of oscillations




ξ = 0
CMB DM DM → $\mu^+\mu^-$
DM DM → e^+e^-
Dwarf DM DM → $\tau^+\tau^-$
DM DM → $b\bar{b}$
GC h DM DM → $b\bar{b}$
δm=10^{-7}eV
δm=10^{-5}eV
r_∞= 124
r_∞= 751
r_∞= 40.8
r_∞= 220
'Standard (η=0)'
Cross Section σ_0[pb]
Dark Matter Mass $m_{\rm DM}$[GeV]
10^2
10
1
10
10^2
10^3
10^4


ξ = 10^{-2}
CMB DM DM → $\mu^+\mu^-$
DM DM → e^+e^-
Dwarf DM DM → $\tau^+\tau^-$
DM DM → $b\bar{b}$
GC h DM DM → $b\bar{b}$
δm=10^{-5}eV
δm=10^{-2}eV
r_∞= 85.3
r_∞= 571
r_∞= 21.9
r_∞= 133
'Standard (η=0)'
Cross Section σ_0[pb]
Dark Matter Mass $m_{\rm DM}$[GeV]
10^2
10
1
10
10^2
10^3
10^4

Conclusion

Wimp physics: a fast-evolving field.

Model builders definitely less free than 10 years ago.

Still a lot more to explore.