

Instituto de Física Teórica, IFT-CSIC Madrid

Marco Taoso

Phenomenology of DM electroweak multiplets

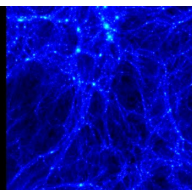
Pascos 2016



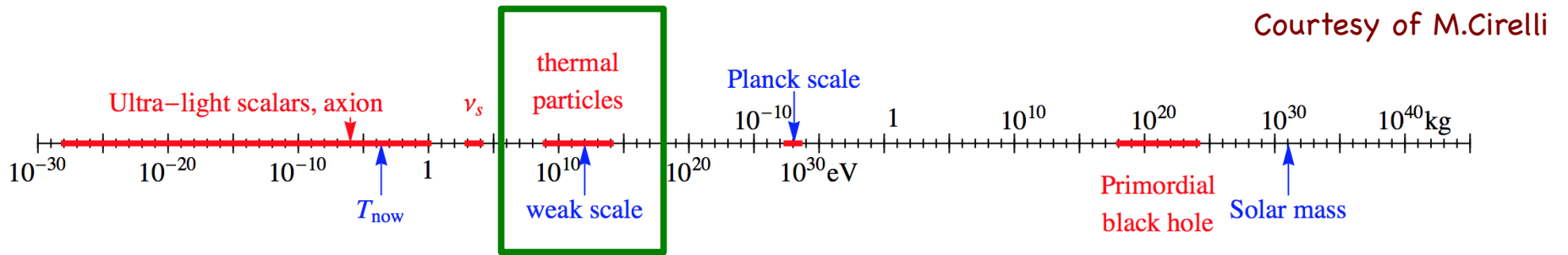
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Quy Nhon
12-07-2016

MultiDark
Multimessenger Approach
for Dark Matter Detection



What do we know about DM?



Courtesy of M.Cirelli

WIMPs often byproducts of Beyond SM theories at the Terascale...

but also independent motivations:

- abundance through thermal decoupling
- multiple way to test the scenario: collider, direct/indirect searches

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13$ TeV

Model	e, μ, τ, γ	Jets	Z, χ^0, χ^\pm	L, τ, ν_τ	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference
MSUGRA/CMSSM	$0-3 e, \mu, 1-2 \tau$	2-10 jets/3 b	Yes	20.3	9.8	1.85 TeV	$m(\tilde{g})=m(\tilde{q})$	1507.0525
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0	2-6 jets	Yes	3.2	610 GeV	890 GeV	$m(\tilde{t}_1)=0 \text{ GeV}, m(\tilde{b}_1)=m(\tilde{\tau}_1)=m(\tilde{\nu}_\tau)=m(\tilde{e}_1)=m(\tilde{\mu}_1)=m(\tilde{\nu}_\tau)=m(\tilde{e}_1)=m(\tilde{\mu}_1))$	ATLAS-CONF-2015-062
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$ (compressed)	0	1-3 jets	Yes	3.2	620 GeV	820 GeV	$m(\tilde{g})=m(\tilde{q})=m(\tilde{q})$	1503.03290
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$ ($\tilde{q} \rightarrow \nu\tilde{\nu}$)	$2 e, \mu$ (off-Z)	2 jets	Yes	20.3	9	1.52 TeV	$m(\tilde{g})=0 \text{ GeV}$	ATLAS-CONF-2015-062
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$ ($\tilde{q} \rightarrow \nu\tilde{\nu}$)	0	2-6 jets	Yes	3.2	9	1.6 TeV	$m(\tilde{t}_1)=0 \text{ GeV}$	ATLAS-CONF-2015-076
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$ ($\tilde{q} \rightarrow \nu\tilde{\nu}$)	$1 e, \mu$	2-6 jets	Yes	3.3	9	1.38 TeV	$m(\tilde{t}_1)=350 \text{ GeV}, m(\tilde{b}_1)=0.5(m(\tilde{t}_1)+m(\tilde{g}))$	1501.03555
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$ ($\tilde{q} \rightarrow \nu\tilde{\nu}$)	$2 e, \mu$	0-3 jets	Yes	20.3	9	1.4 TeV	$m(\tilde{t}_1)=100 \text{ GeV}$	1602.06184
GMSB (\tilde{g} NLSP)	0	7-10 jets	Yes	3.2	9	1.63 TeV	$m(\tilde{g})=0 \text{ GeV}$	1407.0605
GMSB (\tilde{g} NLSP)	$1-2 e + 0-1 \tau$	0-2 jets	Yes	20.3	9	1.34 TeV	$m(\tilde{g})=850 \text{ GeV}, m(\tilde{t}_1)=0.1 \text{ mm}, \mu=0$	1507.05493
GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	9	1.37 TeV	$m(\tilde{t}_1)=350 \text{ GeV}, m(\tilde{b}_1)=0.1 \text{ mm}, \mu=0$	1507.05493
GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	9	1.3 TeV	$m(\tilde{t}_1)=850 \text{ GeV}, m(\tilde{b}_1)=0.1 \text{ mm}, \mu=0$	1507.05493
GGM (higgsino NLSP)	$2 e, \mu$ (Z)	2 jets	Yes	20.3	9	900 GeV	$m(\tilde{g})=300 \text{ GeV}$	1503.03290
Gravitino NLSP	0	mono-jet	Yes	20.3	9	865 GeV	$m(\tilde{g})=1.8 \times 10^{-11} \text{ eV}, m(\tilde{g})=m(\tilde{g})=1.5 \text{ TeV}$	1502.01518
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	0	3 b	Yes	3.3	9	1.76 TeV	$m(\tilde{t}_1)=800 \text{ GeV}$	ATLAS-CONF-2015-067
$\tilde{g}, \tilde{g} \rightarrow t\tilde{t}^*$	$0-1 e, \mu$	3 b	Yes	3.3	9	1.76 TeV	$m(\tilde{t}_1)=0 \text{ GeV}$	To appear
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$0-1 e, \mu$	3 b	Yes	20.1	9	1.37 TeV	$m(\tilde{t}_1)=300 \text{ GeV}$	1407.0606
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	0	2 b	Yes	3.2	9	840 GeV	$m(\tilde{t}_1)=100 \text{ GeV}$	ATLAS-CONF-2015-066
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$2 e, \mu$ (SS)	0-3 b	Yes	3.2	9	335-840 GeV	$m(\tilde{t}_1)=50 \text{ GeV}, m(\tilde{b}_1)=m(\tilde{t}_1)+100 \text{ GeV}$	1502.05055
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$1-2 e, \mu$	1-2 b	Yes	4.7203	9	1170 GeV	$m(\tilde{t}_1)=2m(\tilde{b}_1), m(\tilde{t}_1)=55 \text{ GeV}$	1209.2102, 1407.05563
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$0-2 e, \mu$	0-2 jets+1-2 b	Yes	20.3	9	90-198 GeV	$m(\tilde{t}_1)=1 \text{ GeV}$	1506.08616, ATLAS-CONF-2016-007
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	0	mono-jet+tag	Yes	20.3	9	90-245 GeV	$m(\tilde{t}_1)=m(\tilde{b}_1)=35 \text{ GeV}$	1407.0608
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$2 e, \mu$ (Z)	1 b	Yes	20.3	9	150-600 GeV	$m(\tilde{t}_1)=100 \text{ GeV}$	1403.5222
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$3 e, \mu$ (Z)	1 b	Yes	20.3	9	290-610 GeV	$m(\tilde{t}_1)=200 \text{ GeV}$	1403.5222
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$1 e, \mu$	6 jets + 2 b	Yes	20.3	9	320-620 GeV	$m(\tilde{t}_1)=0 \text{ GeV}$	1506.08616
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$2 e, \mu$	0	Yes	20.3	9	90-335 GeV	$m(\tilde{t}_1)=0 \text{ GeV}$	1403.5294
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$2 e, \mu$	0	Yes	20.3	9	110-475 GeV	$m(\tilde{t}_1)=50 \text{ GeV}, m(\tilde{b}_1)=0.5(m(\tilde{t}_1)+m(\tilde{g}))$	1403.5294
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$2 e, \mu$	0	Yes	20.3	9	335 GeV	$m(\tilde{t}_1)=0 \text{ GeV}, m(\tilde{b}_1)=0.5(m(\tilde{t}_1)+m(\tilde{g}))$	1407.0350
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$3 e, \mu$	0	Yes	20.3	9	425 GeV	$m(\tilde{t}_1)=0, m(\tilde{b}_1)=0.5(m(\tilde{t}_1)+m(\tilde{g}))$	1402.7029
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$2-3 e, \mu$	0-2 jets	Yes	20.3	9	270 GeV	$m(\tilde{t}_1)=m(\tilde{b}_1)=0, \text{ sleptons decoupled}$	1403.5294, 1402.7029
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$4 e, \mu$	0	Yes	20.3	9	425 GeV	$m(\tilde{t}_1)=m(\tilde{b}_1)=0, \text{ sleptons decoupled}$	1501.07110
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$4 e, \mu$	0	Yes	20.3	9	635 GeV	$m(\tilde{t}_1)=m(\tilde{b}_1)=0, m(\tilde{e}_1)=0.5(m(\tilde{t}_1)+m(\tilde{g}))$	1405.5086
GGM (wino NLSP) weak prod.	$1 e, \mu + \gamma$	-	Yes	20.3	9	115-370 GeV	$m(\tilde{t}_1)=0 \text{ GeV}, m(\tilde{b}_1)=0.5(m(\tilde{t}_1)+m(\tilde{g}))$	1507.05493
Direct $\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$ prod. long-lived \tilde{g}	Disapp. trk	1 jet	Yes	20.3	9	270 GeV	$m(\tilde{t}_1)=m(\tilde{b}_1)=160 \text{ MeV}, m(\tilde{g})=0.2 \text{ ns}$	1310.3675
Direct $\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$ prod. long-lived \tilde{g}	dE/dx trk	-	Yes	18.4	9	495 GeV	$m(\tilde{t}_1)=m(\tilde{b}_1)=150 \text{ MeV}, m(\tilde{g})=15 \text{ ns}$	1506.03332
Stable, stopped \tilde{g} R-hadron	0-1-5 jets	-	Yes	27.9	9	850 GeV	$m(\tilde{t}_1)=100 \text{ GeV}, 10 \text{ ps} < \tau < 1000 \text{ s}$	1310.0584
Metastable \tilde{g} R-hadron	dE/dx trk	-	-	3.2	9	9	$m(\tilde{t}_1)=100 \text{ GeV}, \tau > 10 \text{ ns}$	To appear
GMSB, $\tilde{g} \rightarrow q\tilde{g}$, long-lived \tilde{g}	$1-2 \mu$	-	-	19.1	9	537 GeV	$10 \text{ lamp} < \tau < 10 \text{ ns}$	1411.0795
GMSB, $\tilde{g} \rightarrow q\tilde{g}$, long-lived \tilde{g}	2 μ	-	-	20.3	9	440 GeV	$1 < \tau < 10 \text{ ns}$, SPS8 model	1408.0542
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	displ. vtx./jet	-	-	20.3	9	1.0 TeV	$7 < \tau < 740 \text{ mm}, m(\tilde{g})=1.3 \text{ TeV}$	1504.05162
GGM $\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	displ. vtx./jet	-	-	20.3	9	1.0 TeV	$7 < \tau < 740 \text{ mm}, m(\tilde{g})=1.1 \text{ TeV}$	1504.05162
LFV $\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^* + X, X \rightarrow \mu\mu/\tau\tau/\mu\tau$	e, τ, μ, τ	-	-	20.3	9	1.7 TeV	$X_{\mu\mu} < 0.11, X_{\tau\tau} < 0.07$	1503.04330
Bilinear RPV CMSSM	$2 e, \mu$ (SS)	0-3 b	Yes	20.3	9	1.45 TeV	$m(\tilde{t}_1)=m(\tilde{b}_1), \tau_{\tilde{g}} < 1 \text{ mm}$	1404.2500
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$4 e, \mu$	-	-	20.3	9	760 GeV	$m(\tilde{t}_1)=0.2m(\tilde{b}_1), L_{11} > 0$	1405.5096
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$3 e, \mu + \tau$	-	-	20.3	9	450 GeV	$m(\tilde{t}_1)=0.2m(\tilde{b}_1), L_{11} > 0$	1405.5096
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	0	6-7 jets	-	20.3	9	917 GeV	$m(\tilde{t}_1)=0.2m(\tilde{b}_1), L_{11} > 0$	1502.06886
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	0	6-7 jets	-	20.3	9	900 GeV	$m(\tilde{t}_1)=0.2m(\tilde{b}_1), L_{11} > 0$	1502.06886
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$2 e, \mu$ (SS)	0-3 b	Yes	20.3	9	880 GeV	$m(\tilde{t}_1)=0.2m(\tilde{b}_1), L_{11} > 0$	1404.2500
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	0	2 jets + 2 b	-	20.3	9	320 GeV	$m(\tilde{t}_1)=0.2m(\tilde{b}_1), L_{11} > 0$	1501.07455
$\tilde{g}, \tilde{g} \rightarrow b\tilde{b}^*$	$2 e, \mu$	2 b	-	20.3	9	0.4-1.0 TeV	$m(\tilde{t}_1)=0.2m(\tilde{b}_1), L_{11} > 0$	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{c}$	0	2 c	Yes	20.3	510 GeV	$m(\tilde{t}_1)=200 \text{ GeV}$	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown.

An approach to WIMP DM

Minimalistic approach : add to SM an extra gauge multiplet and search for assignments giving a viable DM candidate

This means: stable, neutral and allowed by DM searches.

$$\mathcal{L}_{\text{SM}} + c \begin{cases} \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X} & \text{when } \mathcal{X} \text{ is a spin } 1/2 \text{ fermionic multiplet} \\ |D_\mu \mathcal{X}|^2 - M^2 |\mathcal{X}|^2 & \text{when } \mathcal{X} \text{ is a spin } 0 \text{ bosonic multiplet} \end{cases}$$

The winner is a **fermionic 5plet** (1,5,0).

- Accidental stability if NP scale is at Planck scale
- No Landau poles for the gauge couplings below the cut-off

Minimal Dark Matter

Cirelli, Fornengo, Strumia hep-ph/0512090

If B-L respected also fermionic **3plet** is stable

- capture low-energy pheno of SUSY models with Wino LSP and heavy scalars
- helps with gauge coupling unification in non-SUSY GUTS

Frigerio-Hambye 0912.1545

Relic abundance

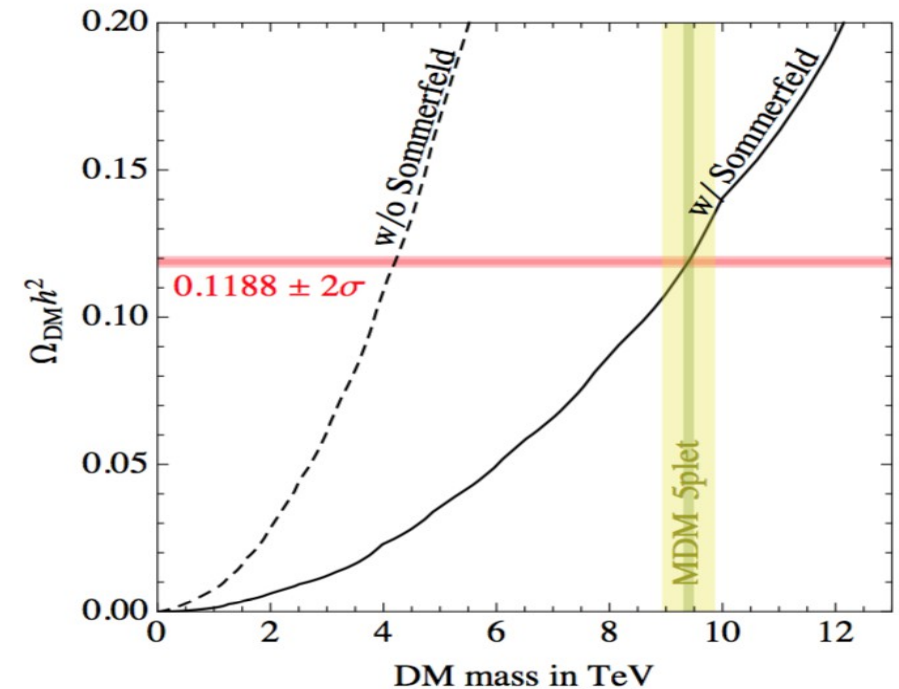
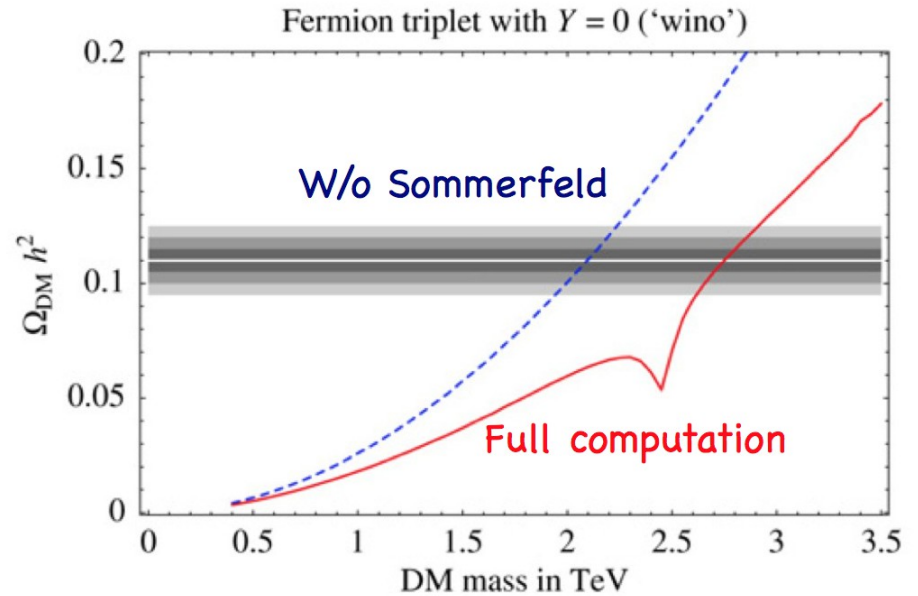
Dominant annihilation channel is WW
 Important to include:

- Coannihilations
- Sommerfeld corrections

Thermal relic mass:

3 TeV 3plet
 10 TeV 5plet

Under-abundant (over-abundant)
 for a larger (smaller) masses

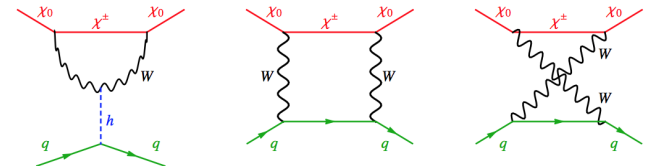


Direct detection

SI cross-section

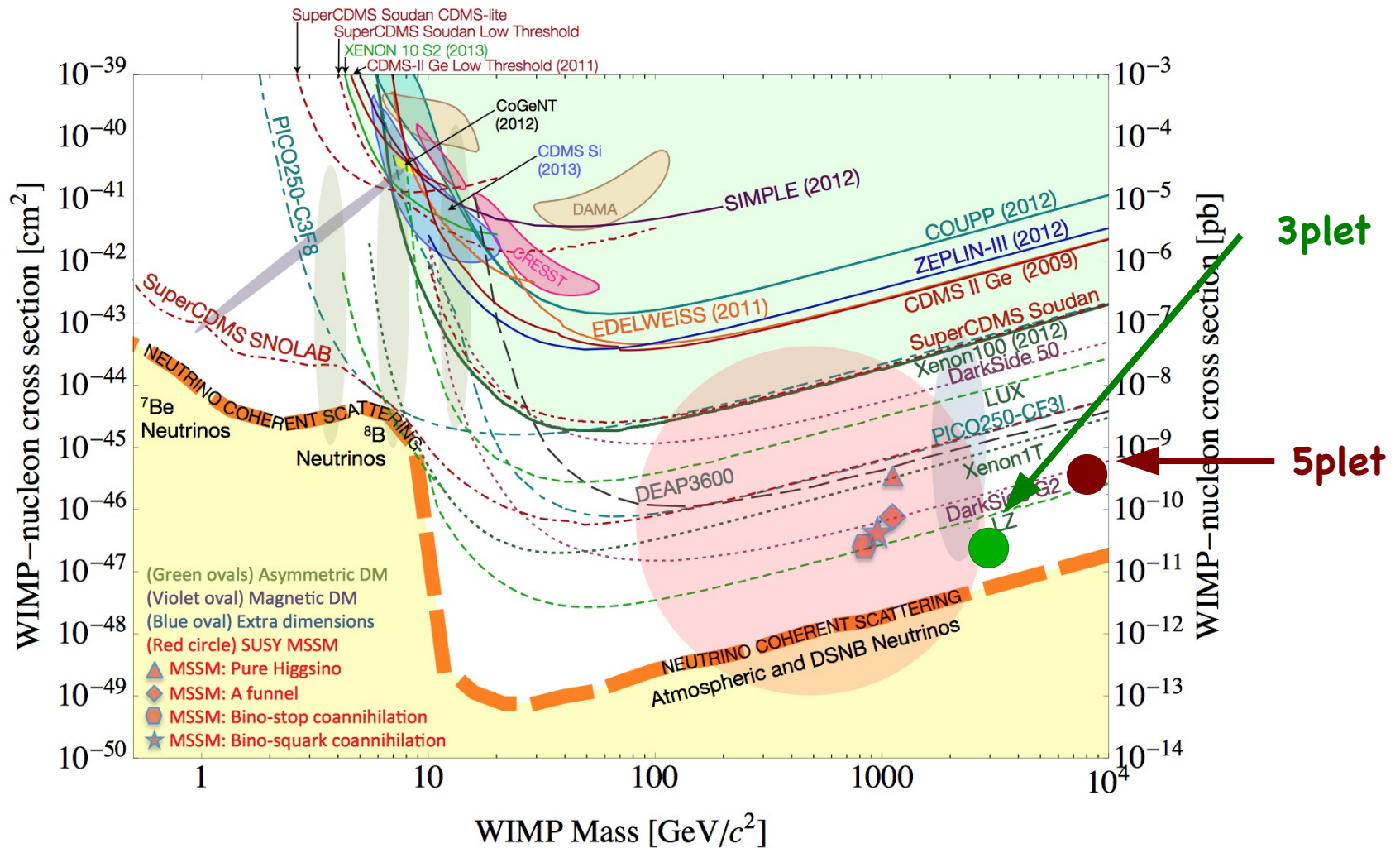
$$\sigma_{SI} = 2.3 \cdot 10^{-47} \text{ cm}^2 \quad \text{3plet}$$

$$\sigma_{SI} = 1.9 \cdot 10^{-46} \text{ cm}^2 \quad \text{5plet}$$



Hisano, Hishiwata, Nagata 1504.00915

Full NLO in α_s



At colliders with disappearing tracks

Mass splitting between charged and neutral components around 165 MeV

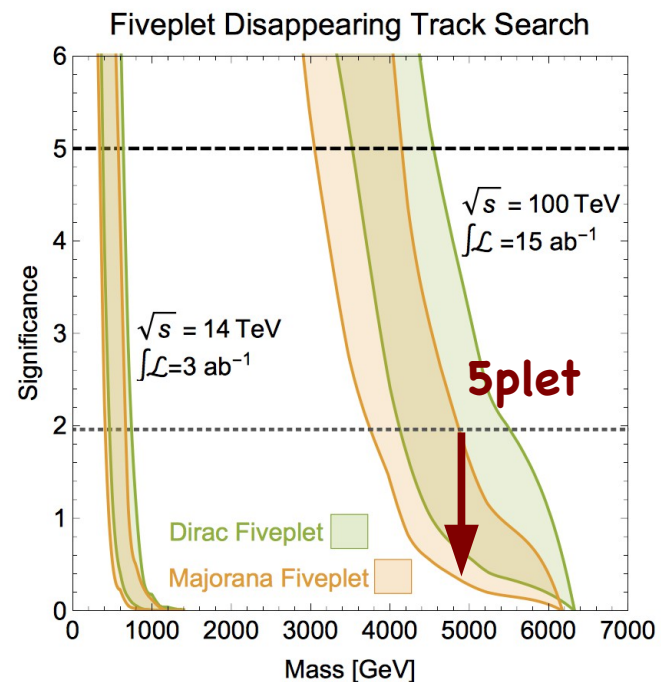
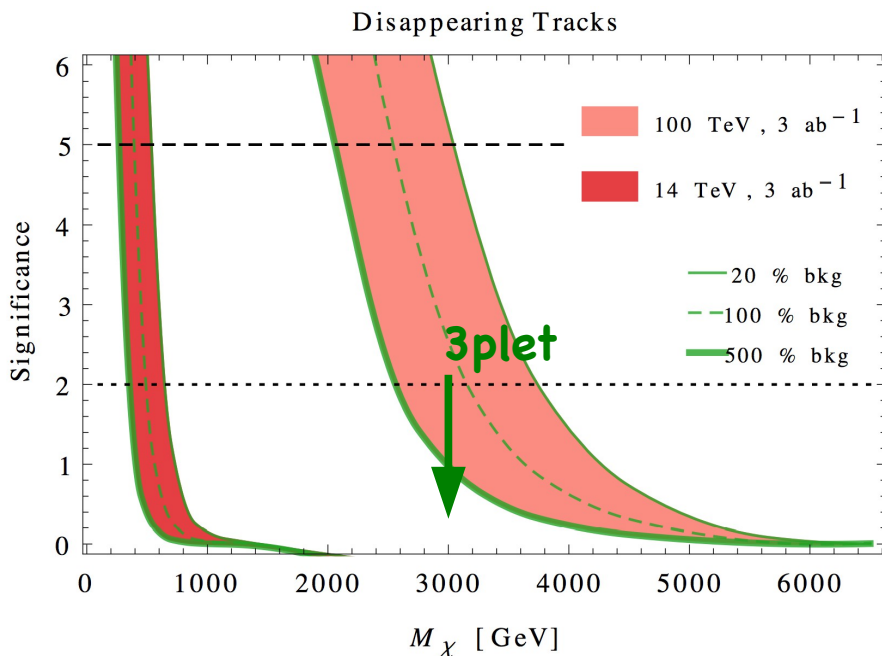
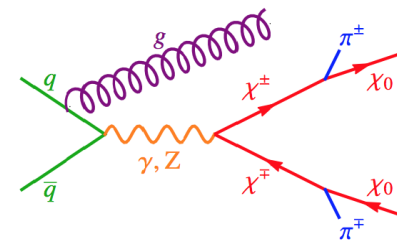
Charged state decays into DM + soft pions

Lifetime of charged particle around 0.2 ns

Charged tracks of ~ 10 cm

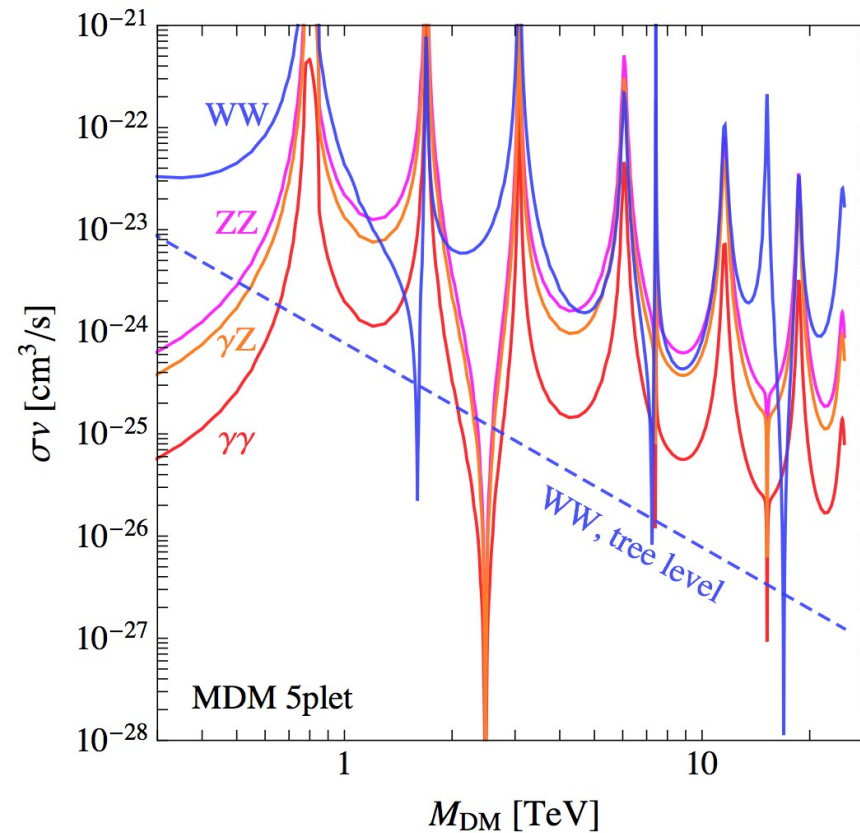
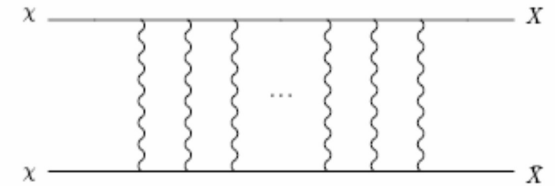
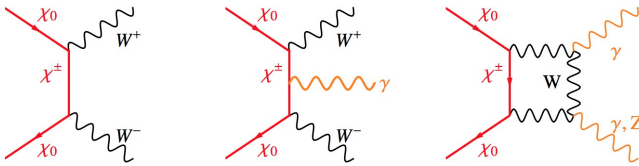
Current ATLAS bounds: $M > 270$ GeV

FCC-hh might probe thermal masses



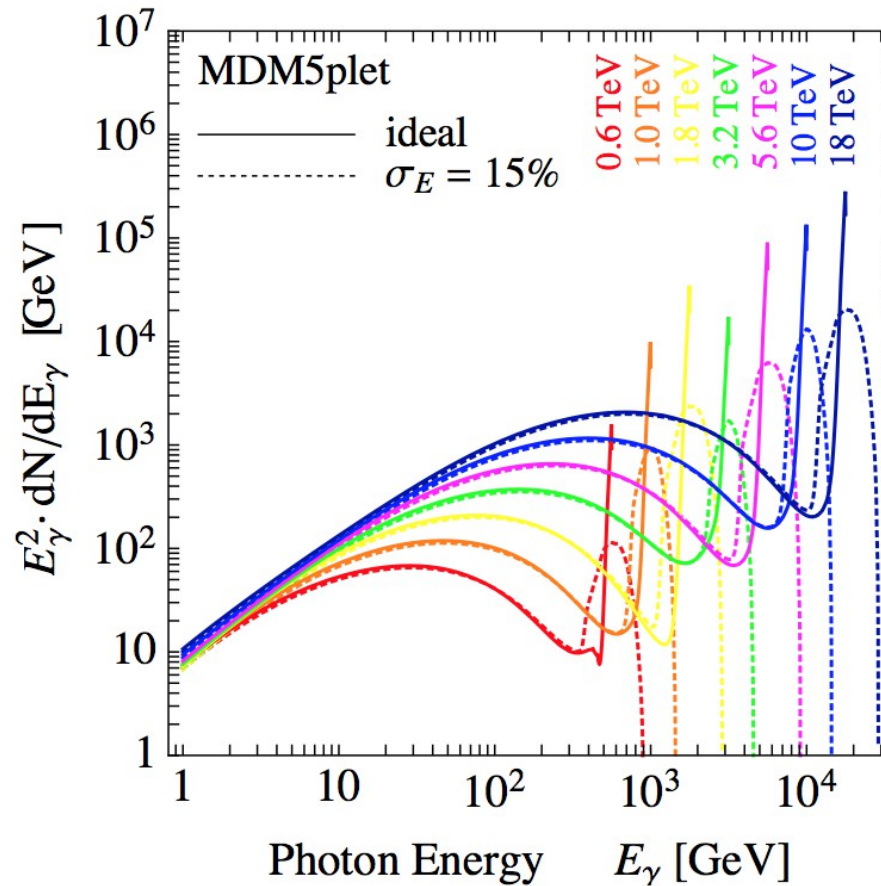
Sommerfeld corrections to annihilations

Non perturbative Sommerfeld corrections relevant at low velocities.
Gauge bosons mediate long range interactions.



Sommerfeld corrections to annihilations

Look for continuum photon emission or feature in energy spectrum (line)



←
Fermi LAT

→
ACT: Hess, Magic,...

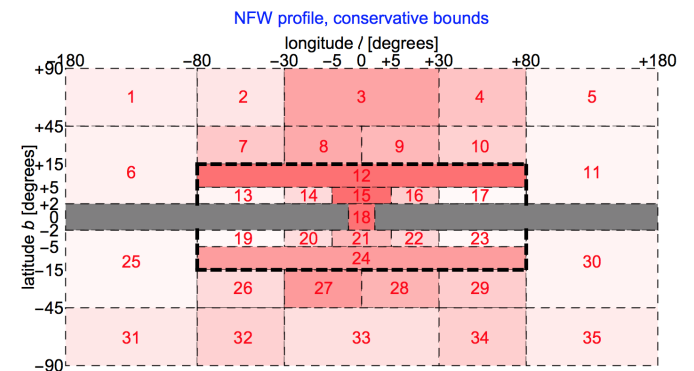
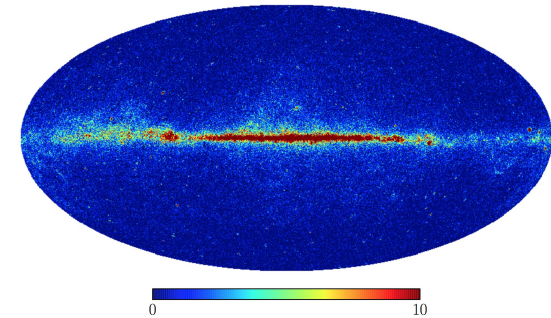
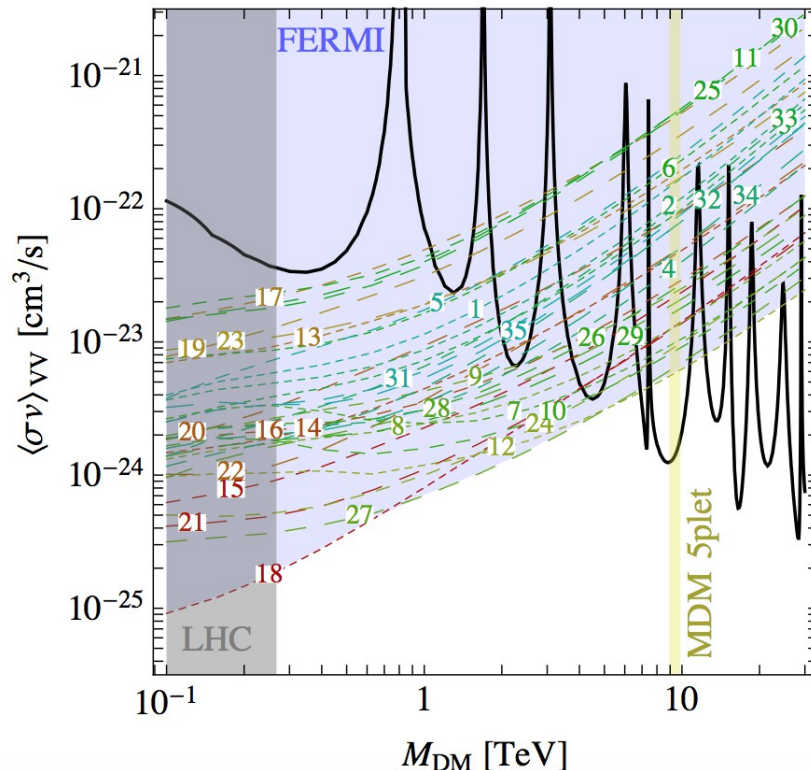
Bounds from gamma-ray observations

Use full-sky Fermi-LAT observations.

Divide sky in non-overlapping ROI and include templates for astro emission:

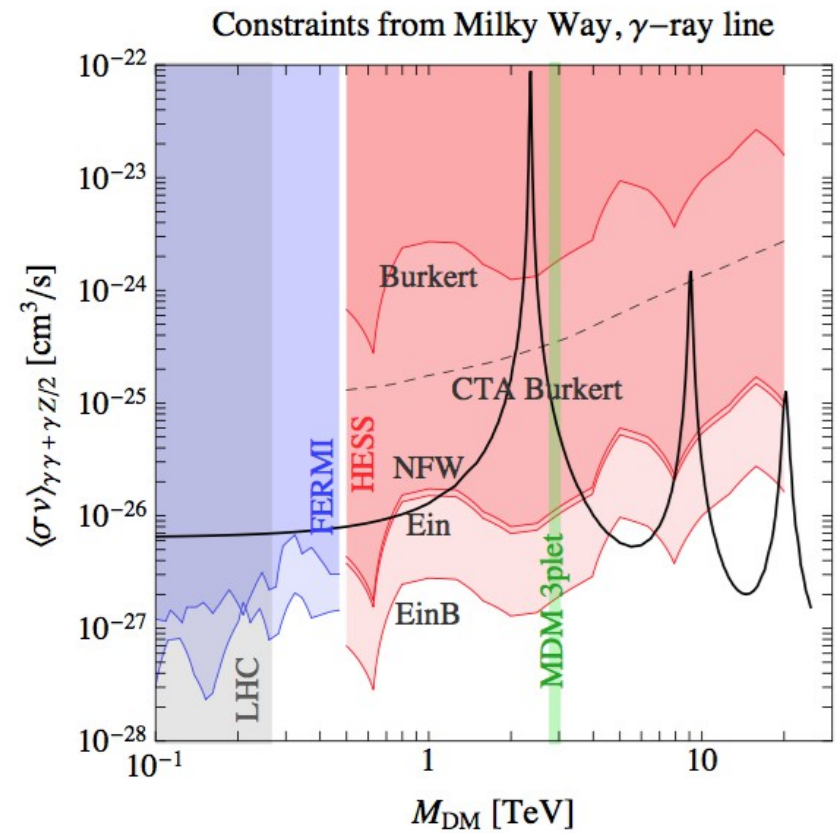
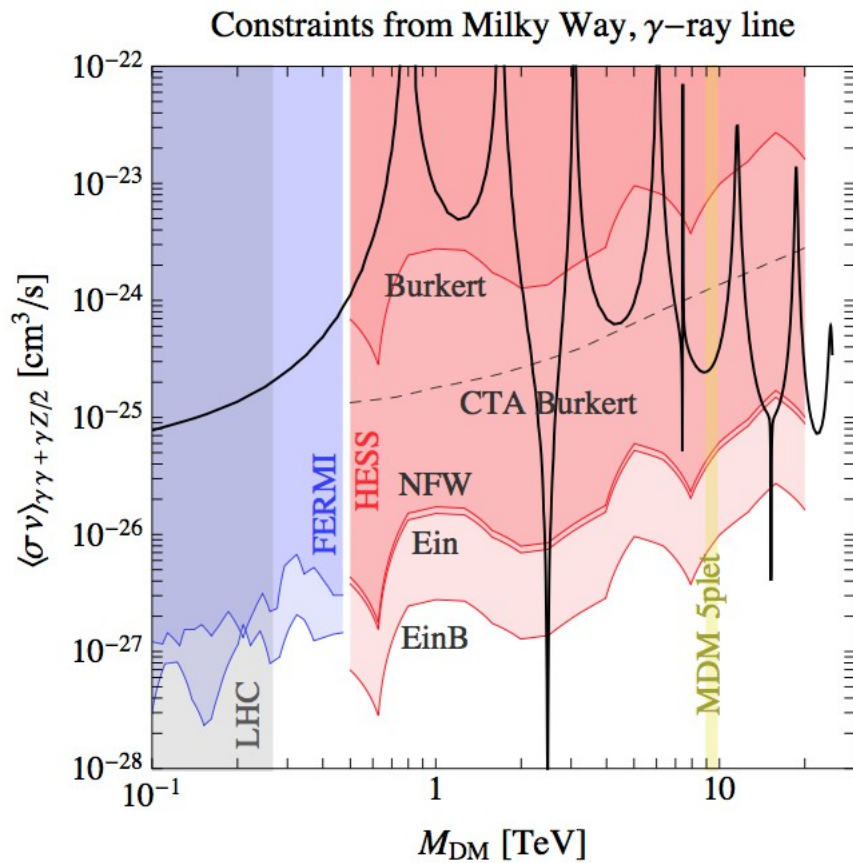
- diffuse emission from CRs
- Fermi bubbles
- Isotropic emission
- Point sources

NFW profile, including background



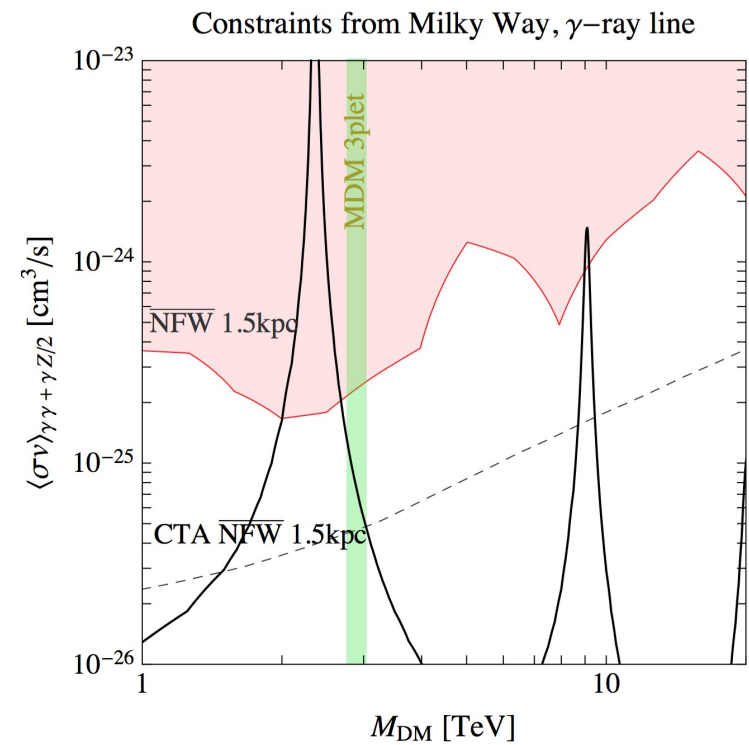
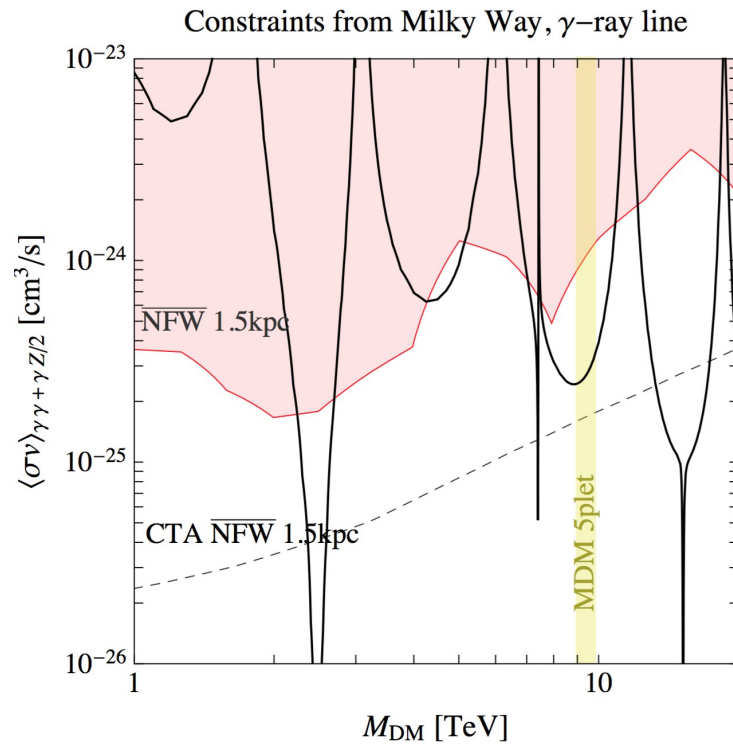
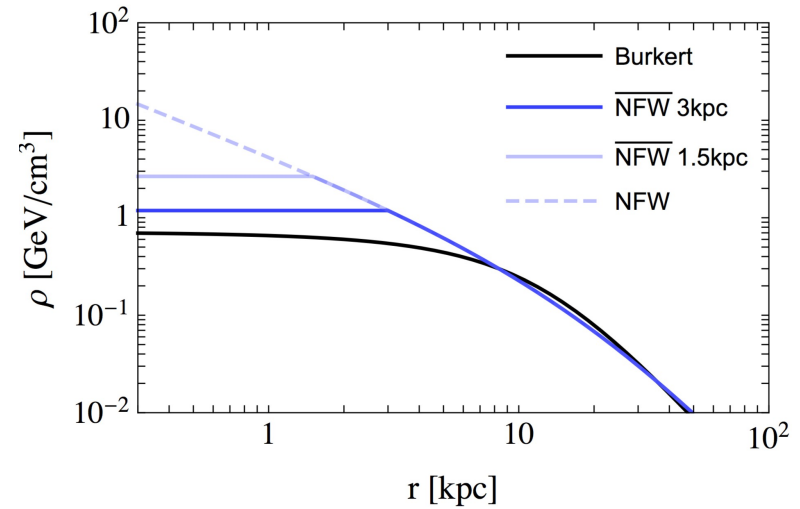
Gamma-ray lines

HESS: small region of observations around GC (1 degree). Huge dependence of bounds on DM density profile



From measurements:
 Density profile unknown in inner few
 kpc region

Pato, Iocco, Bertone 1504.06324

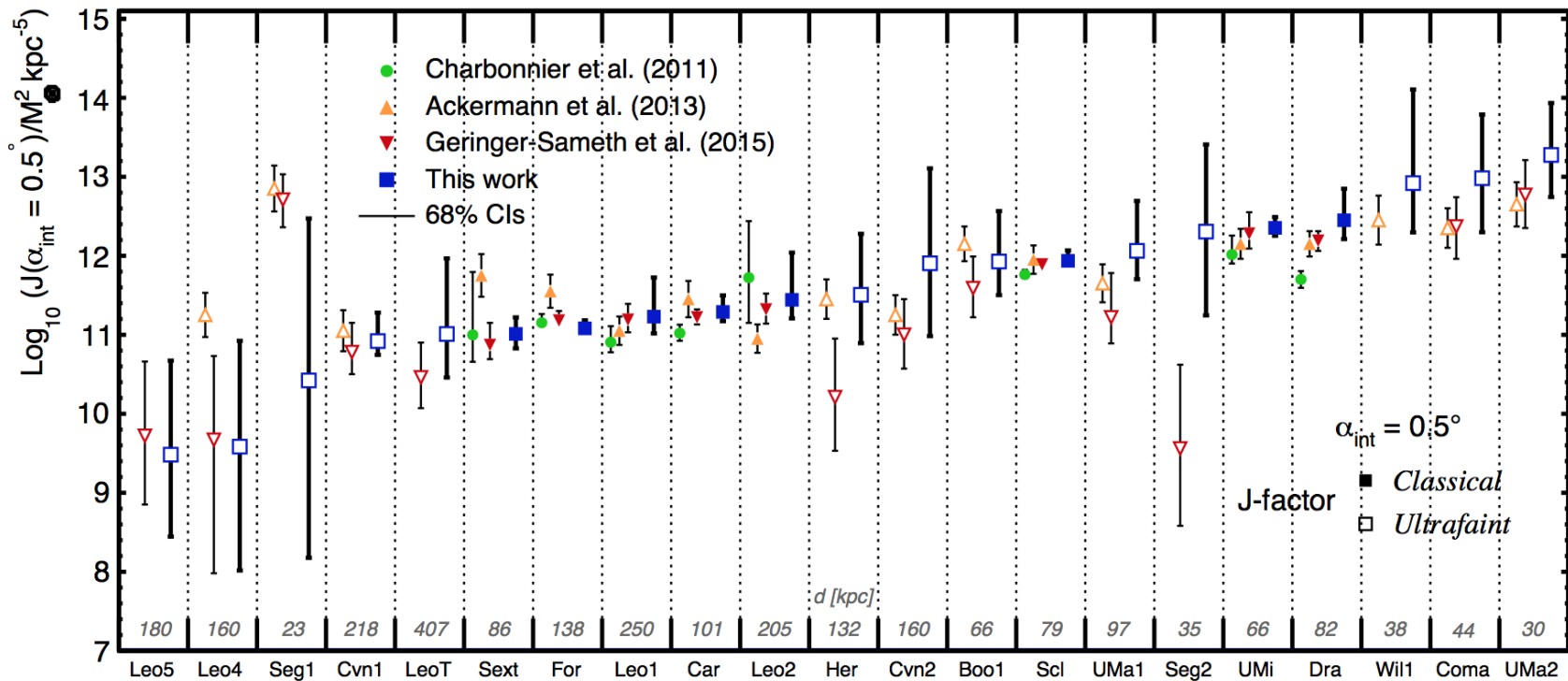


Dwarf galaxies

Close to us, gravitationally dominated by DM, DM density profile reconstructed from star kinematics.

Recent activity to quantify uncertainty on J-factors

e.g. Ullio, Valli 1603.07721, Evans et al. 1604.05599, Genina Fairbairn 1604.00838



Bonnivard et al. 1504.02048

Dwarf galaxies

Fermi-LAT: stacked analysis of 15 dwarves

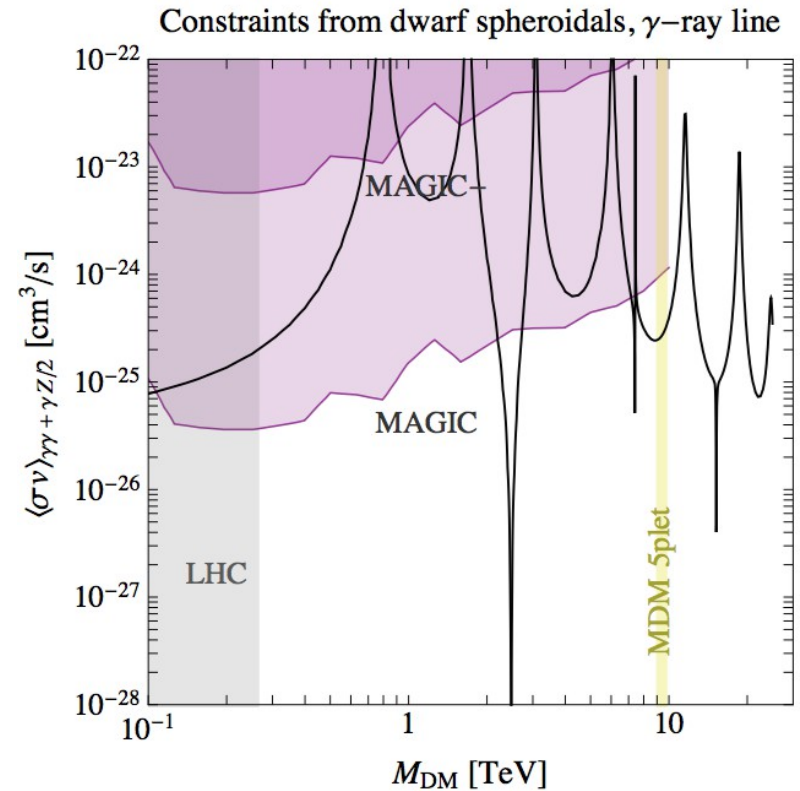
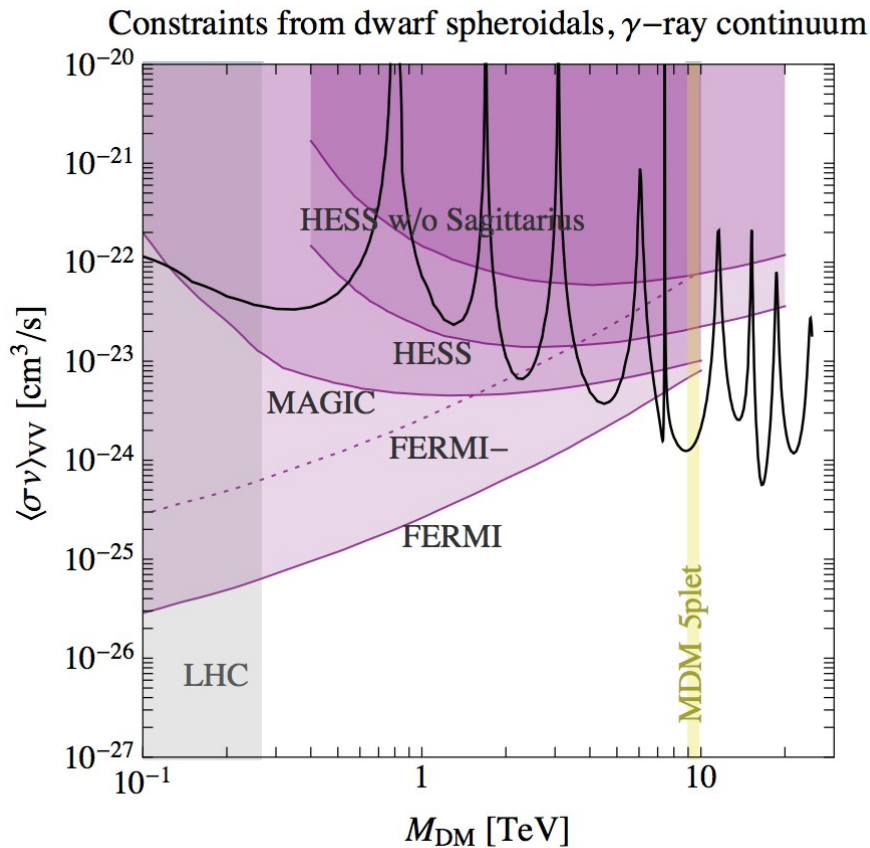
HESS: 4 dwarves

MAGIC: only Segue 1. Current uncertainty on J-factor is large for this dwarf

HESS obs of dwarfs could be used also for lines!

Ongoing analysis:

Hess collaboration + Cirelli, Panci, Sala, Silk, MT

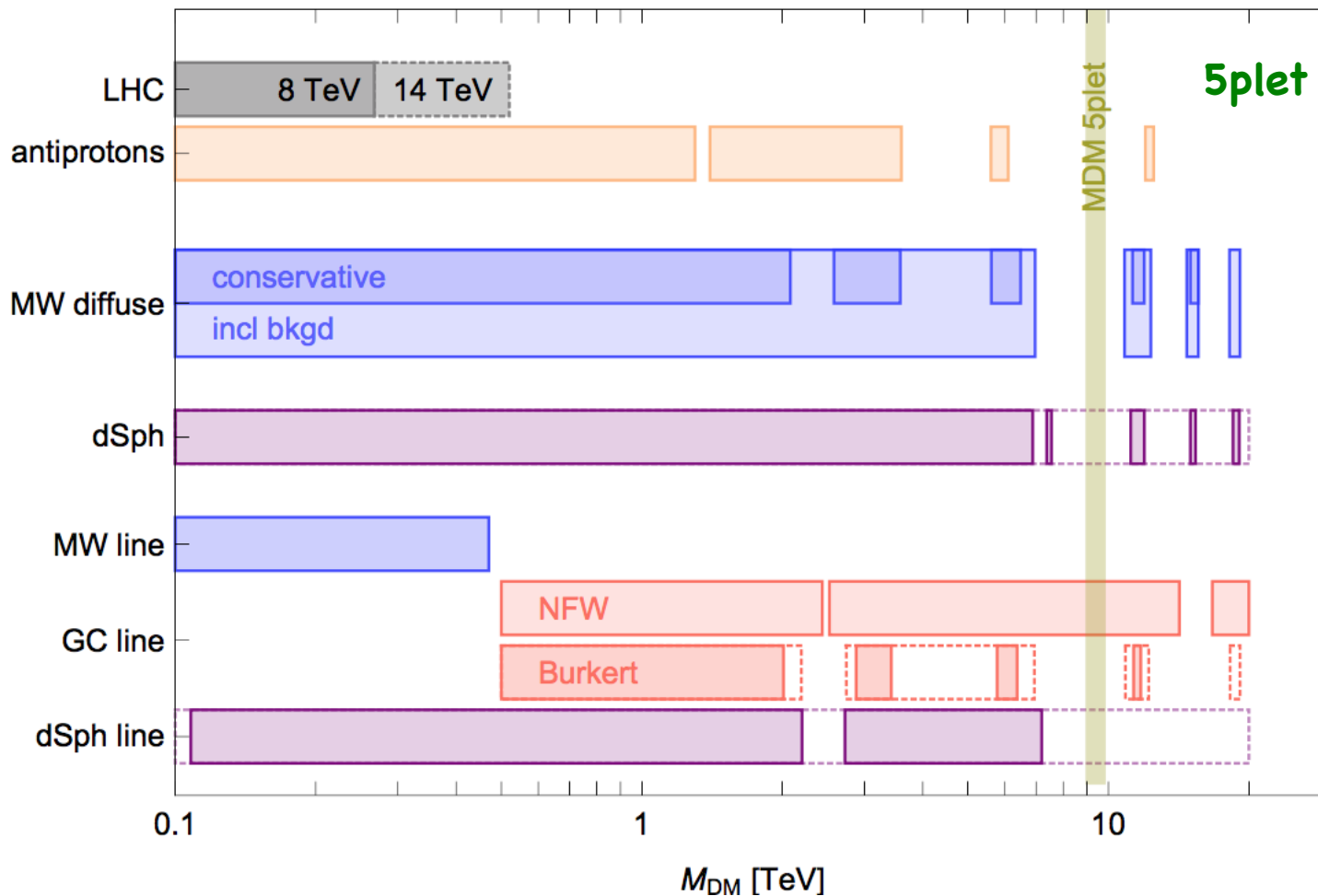


Summary

Lines from inner galaxies good probe of 3-plet and 5-plet but large uncertainties.

Obs. Of dwarf galaxies look promising and significant progress may come in near future.

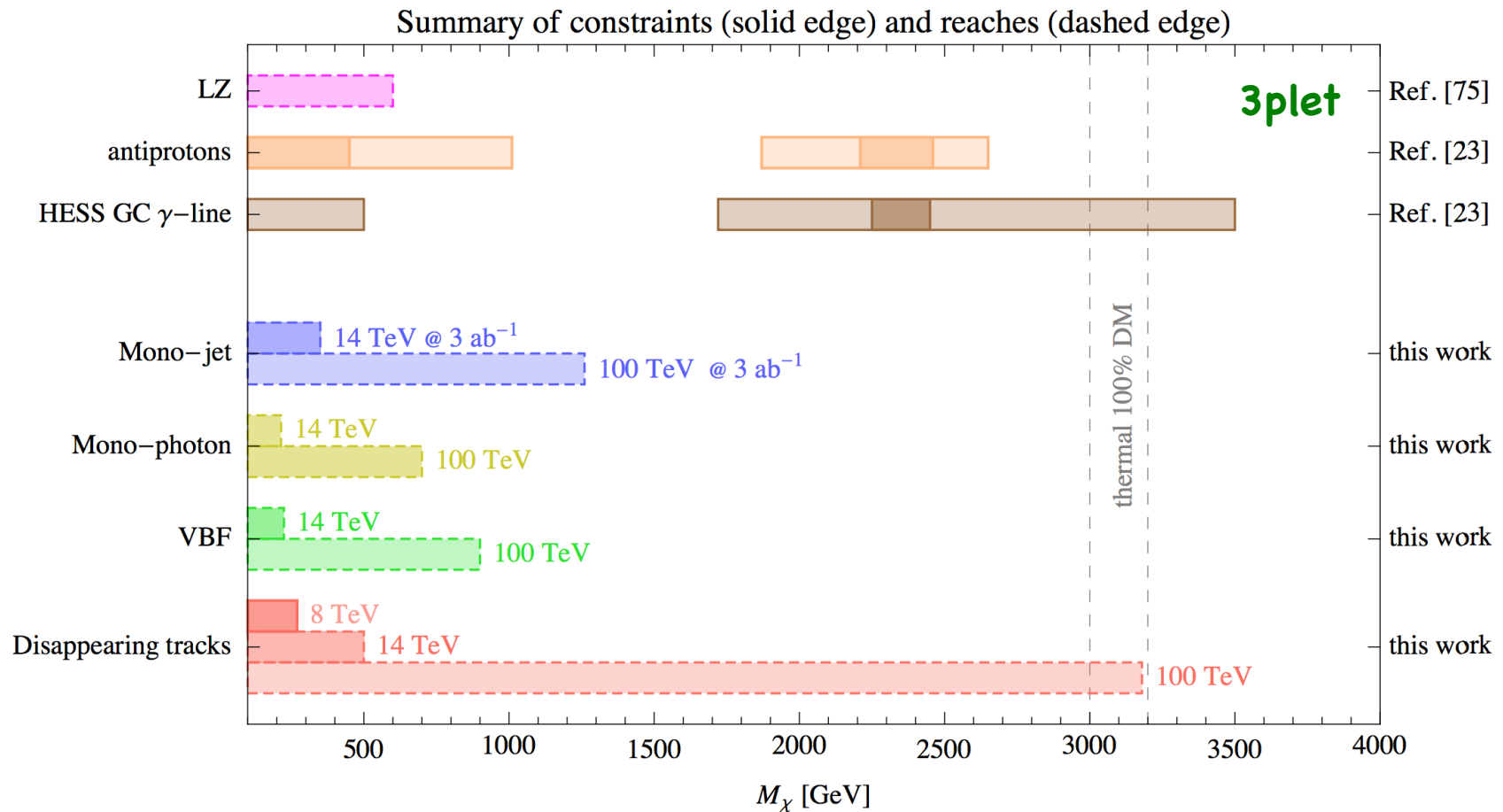
Summary of constraints (solid edge) and reaches (dashed edge)



Summary

Lines from inner galaxies good probe of 3-plet and 5-plet but large uncertainties.

Obs. Of dwarf galaxies look promising and significant progress may come in near future.



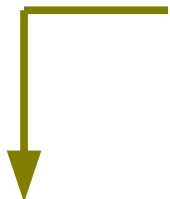
Thanks!

THANKS

Minimal Dark Matter

From Cirelli, Strumia 0903.3381

Quantum numbers			DM can decay into	DD bound?	Stable?
SU(2) _L	U(1) _Y	Spin			
2	1/2	<i>S</i>	<i>EL</i>	×	×
2	1/2	<i>F</i>	<i>EH</i>	×	×
3	0	<i>S</i>	<i>HH*</i>	✓	×
3	0	<i>F</i>	<i>LH</i>	✓	×
3	1	<i>S</i>	<i>HH, LL</i>	×	×
3	1	<i>F</i>	<i>LH</i>	×	×
4	1/2	<i>S</i>	<i>HHH*</i>	×	×
4	1/2	<i>F</i>	(<i>LHH*</i>)	×	×
4	3/2	<i>S</i>	<i>HHH</i>	×	×
4	3/2	<i>F</i>	(<i>LHH</i>)	×	×
5	0	<i>S</i>	(<i>HHH*H*</i>)	✓	×
5	0	<i>F</i>	—	✓	✓
5	1	<i>S</i>	(<i>HH*H*H*</i>)	×	×
5	1	<i>F</i>	—	×	✓
5	2	<i>S</i>	(<i>H*H*H*H*</i>)	×	×
5	2	<i>F</i>	—	×	✓
6	1/2, 3/2, 5/2	<i>S</i>	—	×	✓
7	0	<i>S</i>	—	✓	✓
8	1/2, 3/2 ...	<i>S</i>	—	×	✓



7-plet not stable Di Luzio et al. 1504.00359

Disappearing tracks

Lifetime of charged particle around 0.2 ns
 Charged tracks of ~ 10 cm

Backgrounds:

- interactions of charged hadrons in the detector
- unidentified leptons
- pT mis-measured tracks (dominant at large pT)

ATLAS 8 TEV with 20 fb^{-1}

Bound $M > 270 \text{ GeV}$ (95% CL)

