# Neutrino lines and gamma-ray spectral features in indirect searches of dark matter

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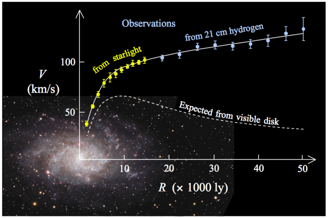
Based on JCAP 1703 (2017) no.03, 054 , JCAP 1603 (2016) 021, JCAP 1510 (2015) no.10, 058, arXiv:1701.07209.

# Outline

- Motivation
- Part I: Gamma-ray spectral features in indirect dark matter searches
- Part II: Neutrino lines in indirect dark matter searches

# Evidence for Dark Matter



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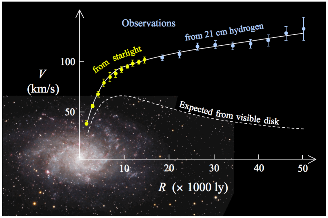

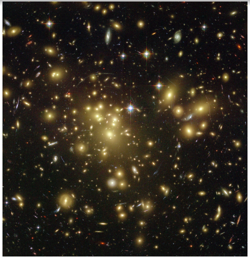

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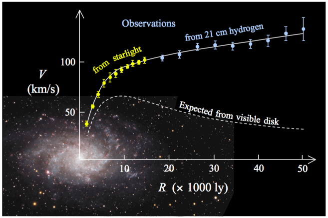

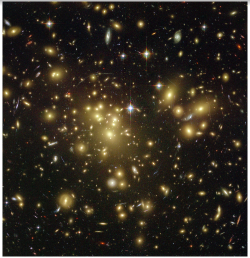

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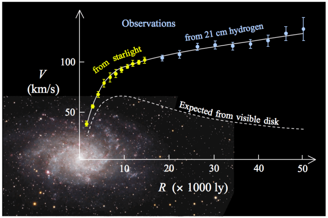

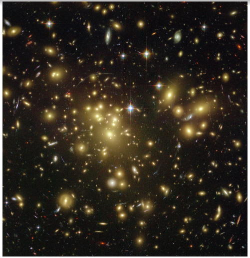

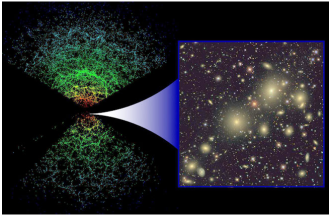

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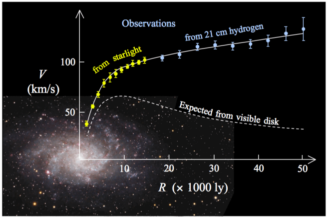

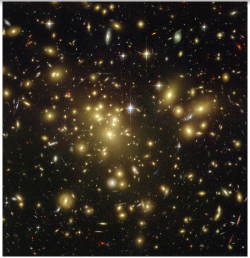

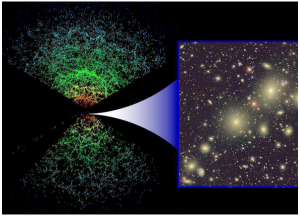

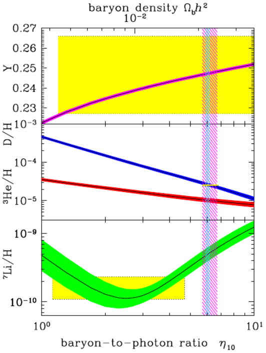

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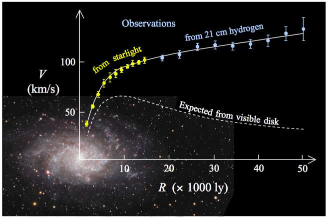
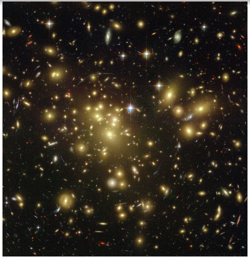
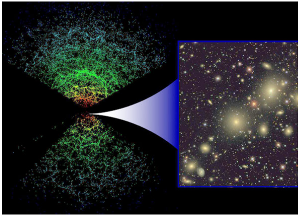
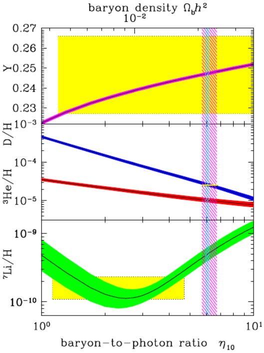
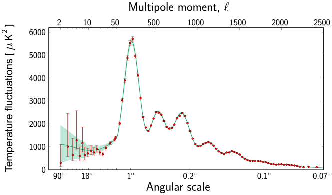






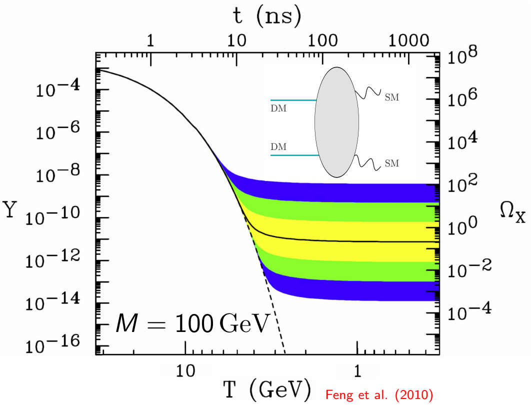




# Weakly Interactive Massive Particles (WIMPs)

## WIMP Paradigm

Lee and Weinberg (1977)



Feng et al. (2010)

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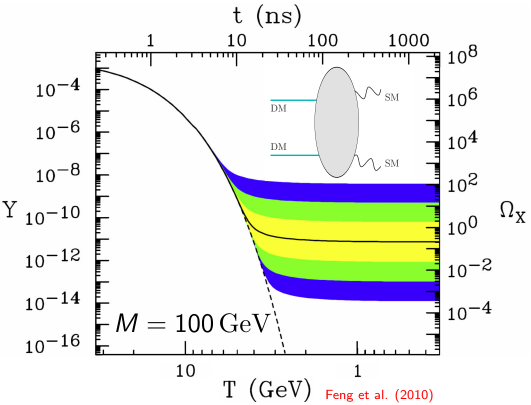

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$$\Omega h^2 = \frac{0.1\,\mathrm{pb}}{\sigma v}$$

$$\sigma v \sim \frac{g^4}{M^2} \sim 1\,\mathrm{pb}$$

$$M \sim 100\,\mathrm{GeV}\ \text{to}\ 200\,\mathrm{TeV}$$

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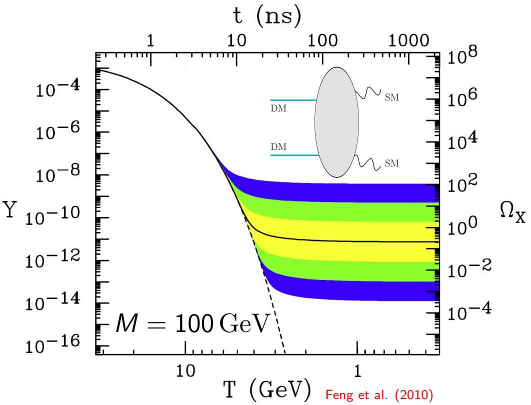

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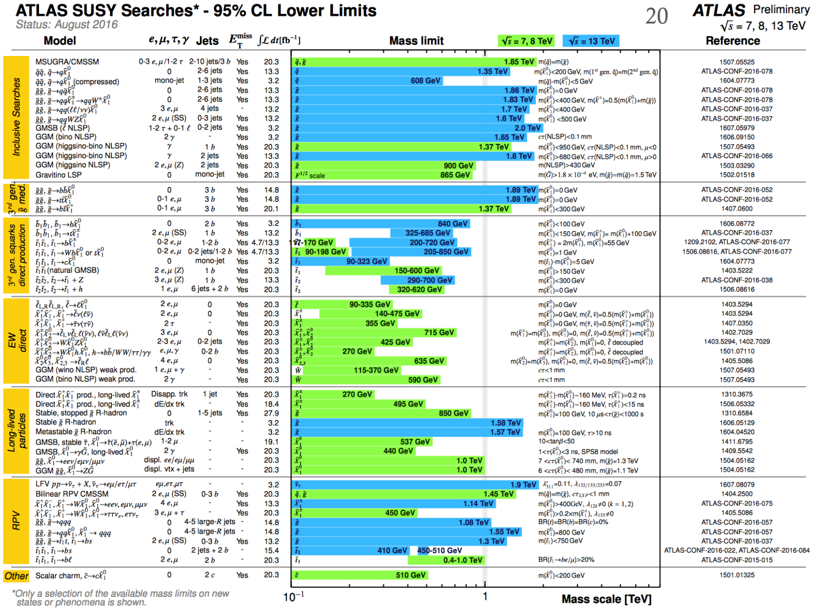
Griest and Kamionkowski(1990)

# Searches for WIMP particles



**ATLAS SUSY Searches* - 95% CL Lower Limits**

*Status: August 2016*

20

**ATLAS** Preliminary

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

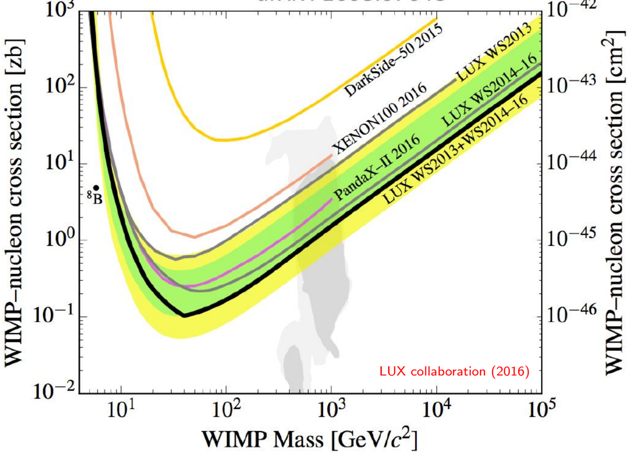
🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

| | Model | $e,\mu,\tau,\gamma$ | Jets | $E_T^{miss}$ | $\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$ | Mass limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Inclusive Searches | MSUGRA/CMSSM | 0-3 $e,\mu$/1-2 $\tau$ | 2-10 jets/3 $b$ | Yes | 20.3 | $\tilde q,\tilde g$ 1.85 TeV | $m(\tilde q)$=$m(\tilde g)$ | 1507.05525 |
| | $\tilde q\tilde q$, $\tilde q\to q\tilde\chi^0_1$ | 0 | 2-6 jets | Yes | 13.3 | $\tilde q$ 1.35 TeV | $m(\tilde\chi^0_1)$<200 GeV, m(1st gen. $\tilde q$)=m(2nd gen. $\tilde q$) | ATLAS-CONF-2016-078 |
| | $\tilde q\tilde q$, $\tilde q\to q\tilde\chi^0_1$ (compressed) | mono-jet | 1-3 jets | Yes | 3.2 | $\tilde q$ 608 GeV | $m(\tilde q)$-$m(\tilde\chi^0_1)$<5 GeV | 1604.07773 |
| | $\tilde g\tilde g$, $\tilde g\to q\bar q\tilde\chi^0_1$ | 0 | 2-6 jets | Yes | 13.3 | $\tilde g$ 1.86 TeV | $m(\tilde\chi^0_1)$=0 GeV | ATLAS-CONF-2016-078 |
| | $\tilde g\tilde g$, $\tilde g\to qq\tilde\chi^\pm_1\to qqW^\pm\tilde\chi^0_1$ | 0 | 2-6 jets | Yes | 13.3 | $\tilde g$ 1.83 TeV | $m(\tilde\chi^0_1)$<400 GeV, $m(\tilde\chi^\pm)$=0.5($m(\tilde\chi^0_1)$+$m(\tilde g)$) | ATLAS-CONF-2016-078 |
| | $\tilde g\tilde g$, $\tilde g\to qq(\ell\ell/\nu\nu)\tilde\chi^0_1$ | 3 $e,\mu$ | 4 jets | - | 13.2 | $\tilde g$ 1.7 TeV | $m(\tilde\chi^0_1)$<400 GeV | ATLAS-CONF-2016-037 |
| | $\tilde g\tilde g$, $\tilde g\to qqWZ\tilde\chi^0_1$ | 2 $e,\mu$ (SS) | 0-3 jets | Yes | 13.2 | $\tilde g$ 1.6 TeV | $m(\tilde\chi^0_1)$ <500 GeV | ATLAS-CONF-2016-037 |
| | GMSB ($\tilde\ell$ NLSP) | 1-2 $\tau$ + 0-1 $\ell$ | 0-2 jets | Yes | 3.2 | $\tilde g$ 2.0 TeV | | 1607.05979 |
| | GGM (bino NLSP) | 2 $\gamma$ | - | Yes | 3.2 | $\tilde g$ 1.65 TeV | $c\tau$(NLSP)<0.1 mm | 1606.09150 |
| | GGM (higgsino-bino NLSP) | $\gamma$ | 1 $b$ | Yes | 20.3 | $\tilde g$ 1.37 TeV | $m(\tilde\chi^0_1)$<950 GeV, $c\tau$(NLSP)<0.1 mm, $\mu$<0 | 1507.05493 |
| | GGM (higgsino-bino NLSP) | $\gamma$ | 2 jets | Yes | 13.3 | $\tilde g$ 1.8 TeV | $m(\tilde\chi^0_1)$>680 GeV, $c\tau$(NLSP)<0.1 mm, $\mu$>0 | ATLAS-CONF-2016-066 |
| | GGM (higgsino NLSP) | 2 $e,\mu$ ($Z$) | 2 jets | Yes | 20.3 | $\tilde g$ 900 GeV | m(NLSP)>430 GeV | 1503.03290 |
| | Gravitino LSP | 0 | mono-jet | Yes | 20.3 | $F^{1/2}$ scale 865 GeV | $m(\tilde G)$>1.8 × $10^{-4}$ eV, $m(\tilde g)$=$m(\tilde q)$=1.5 TeV | 1502.01518 |
| 3rd gen. $\tilde g$ med. | $\tilde g\tilde g$, $\tilde g\to b\bar b\tilde\chi^0_1$ | 0 | 3 $b$ | Yes | 14.8 | $\tilde g$ 1.89 TeV | $m(\tilde\chi^0_1)$=0 GeV | ATLAS-CONF-2016-052 |
| | $\tilde g\tilde g$, $\tilde g\to t\bar t\tilde\chi^0_1$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 14.8 | $\tilde g$ 1.89 TeV | $m(\tilde\chi^0_1)$=0 GeV | ATLAS-CONF-2016-052 |
| | $\tilde g\tilde g$, $\tilde g\to b\bar t\tilde\chi^+_1$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 20.1 | $\tilde g$ 1.37 TeV | $m(\tilde\chi^0_1)$<300 GeV | 1407.0600 |
| 3rd gen. squarks direct production | $\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi^0_1$ | 0 | 2 $b$ | Yes | 3.2 | $\tilde b_1$ 840 GeV | $m(\tilde\chi^0_1)$<100 GeV | 1606.08772 |
| | $\tilde b_1\tilde b_1$, $\tilde b_1\to t\tilde\chi^\pm_1$ | 2 $e,\mu$ (SS) | 1 $b$ | Yes | 13.2 | $\tilde b_1$ 325-685 GeV | $m(\tilde\chi^0_1)$<150 GeV, $m(\tilde\chi^\pm_1)$= $m(\tilde\chi^0_1)$+100 GeV | ATLAS-CONF-2016-037 |
| | $\tilde t_1\tilde t_1$, $\tilde t_1\to b\tilde\chi^\pm_1$ | 0-2 $e,\mu$ | 1-2 $b$ | Yes | 4.7/13.3 | $\tilde t_1$ 117-170 GeV<br>200-720 GeV | $m(\tilde\chi^\pm_1)$ = 2$m(\tilde\chi^0_1)$, $m(\tilde\chi^0_1)$=55 GeV | 1209.2102, ATLAS-CONF-2016-077 |
| | $\tilde t_1\tilde t_1$, $\tilde t_1\to Wb\tilde\chi^0_1$ or $t\tilde\chi^0_1$ | 0-2 $e,\mu$ | 0-2 jets/1-2 $b$ | Yes | 4.7/13.3 | $\tilde t_1$ 90-198 GeV<br>205-850 GeV | $m(\tilde\chi^0_1)$=1 GeV | 1506.08616, ATLAS-CONF-2016-077 |
| | $\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi^0_1$ | 0 | mono-jet | Yes | 3.2 | $\tilde t_1$ 90-323 GeV | $m(\tilde t_1)$-$m(\tilde\chi^0_1)$=5 GeV | 1604.07773 |
| | $\tilde t_1\tilde t_1$(natural GMSB) | 2 $e,\mu$ ($Z$) | 1 $b$ | Yes | 20.3 | $\tilde t_1$ 150-600 GeV | $m(\tilde\chi^0_1)$>150 GeV | 1403.5222 |
| | $\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1+Z$ | 3 $e,\mu$ ($Z$) | 1 $b$ | Yes | 13.3 | $\tilde t_2$ 290-700 GeV | $m(\tilde\chi^0_1)$<300 GeV | ATLAS-CONF-2016-038 |
| | $\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1+h$ | 1 $e,\mu$ | 6 jets + 2 $b$ | Yes | 20.3 | $\tilde t_2$ 320-620 GeV | $m(\tilde\chi^0_1)$=0 GeV | 1506.08616 |
| EW direct | $\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell\to\ell\tilde\chi^0_1$ | 2 $e,\mu$ | 0 | Yes | 20.3 | $\tilde\ell$ 90-335 GeV | $m(\tilde\chi^0_1)$=0 GeV | 1403.5294 |
| | $\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to\tilde\ell\nu(\ell\tilde\nu)$ | 2 $e,\mu$ | 0 | Yes | 20.3 | $\tilde\chi^\pm_1$ 140-475 GeV | $m(\tilde\chi^0_1)$=0 GeV, $m(\tilde\ell,\tilde\nu)$=0.5($m(\tilde\chi^\pm_1)$+$m(\tilde\chi^0_1)$) | 1403.5294 |
| | $\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to\tilde\tau\nu(\tau\tilde\nu)$ | 2 $\tau$ | - | Yes | 20.3 | $\tilde\chi^\pm_1$ 355 GeV | $m(\tilde\chi^0_1)$=0 GeV, $m(\tilde\tau,\tilde\nu)$=0.5($m(\tilde\chi^\pm_1)$+$m(\tilde\chi^0_1)$) | 1407.0350 |
| | $\tilde\chi^\pm_1\tilde\chi^0_2\to\tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu)$, $\ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$ | 3 $e,\mu$ | 0 | Yes | 20.3 | $\tilde\chi^\pm_1,\tilde\chi^0_2$ 715 GeV | $m(\tilde\chi^\pm_1)$=$m(\tilde\chi^0_2)$, $m(\tilde\chi^0_1)$=0, $m(\tilde\ell,\tilde\nu)$=0.5($m(\tilde\chi^\pm_1)$+$m(\tilde\chi^0_1)$) | 1402.7029 |
| | $\tilde\chi^\pm_1\tilde\chi^0_2\to W\tilde\chi^0_1Z\tilde\chi^0_1$ | 2-3 $e,\mu$ | 0-2 jets | Yes | 20.3 | $\tilde\chi^\pm_1,\tilde\chi^0_2$ 425 GeV | $m(\tilde\chi^\pm_1)$=$m(\tilde\chi^0_2)$, $m(\tilde\chi^0_1)$=0, $\tilde\ell$ decoupled | 1403.5294, 1402.7029 |
| | $\tilde\chi^\pm_1\tilde\chi^0_2\to W\tilde\chi^0_1h\tilde\chi^0_1$, $h\to b\bar b/WW/\tau\tau/\gamma\gamma$ | $e,\mu,\gamma$ | 0-2 $b$ | Yes | 20.3 | $\tilde\chi^\pm_1,\tilde\chi^0_2$ 270 GeV | $m(\tilde\chi^\pm_1)$=$m(\tilde\chi^0_2)$, $m(\tilde\chi^0_1)$=0, $\tilde\ell$ decoupled | 1501.07110 |
| | $\tilde\chi^0_2\tilde\chi^0_3$, $\tilde\chi^0_{2,3}\to\tilde\ell_R\ell$ | 4 $e,\mu$ | 0 | Yes | 20.3 | $\tilde\chi^0_{2,3}$ 635 GeV | $m(\tilde\chi^0_2)$=$m(\tilde\chi^0_3)$, $m(\tilde\chi^0_1)$=0, $m(\tilde\ell,\tilde\nu)$=0.5($m(\tilde\chi^0_2)$+$m(\tilde\chi^0_1)$) | 1405.5086 |
| | GGM (wino NLSP) weak prod. | 1 $e,\mu$ + $\gamma$ | - | Yes | 20.3 | $\tilde W$ 115-370 GeV | $c\tau$<1 mm | 1507.05493 |
| | GGM (bino NLSP) weak prod. | 2 $\gamma$ | - | Yes | 20.3 | $\tilde W$ 590 GeV | $c\tau$<1 mm | 1507.05493 |
| Long-lived particles | Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$ | Disapp. trk | 1 jet | Yes | 20.3 | $\tilde\chi^\pm_1$ 270 GeV | $m(\tilde\chi^\pm_1)$-$m(\tilde\chi^0_1)$~160 MeV, $\tau(\tilde\chi^\pm_1)$=0.2 ns | 1310.3675 |
| | Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$ | dE/dx trk | - | Yes | 18.4 | $\tilde\chi^\pm_1$ 495 GeV | $m(\tilde\chi^\pm_1)$-$m(\tilde\chi^0_1)$~160 MeV, $\tau(\tilde\chi^\pm_1)$<15 ns | 1506.05332 |
| | Stable, stopped $\tilde g$ R-hadron | 0 | 1-5 jets | Yes | 27.9 | $\tilde g$ 850 GeV | $m(\tilde\chi^0_1)$=100 GeV, 10 $\mu s$<$\tau(\tilde g)$<1000 s | 1310.6584 |
| | Stable $\tilde g$ R-hadron | trk | - | - | 3.2 | $\tilde g$ 1.58 TeV | | 1606.05129 |
| | Metastable $\tilde g$ R-hadron | dE/dx trk | - | - | 3.2 | $\tilde g$ 1.57 TeV | $m(\tilde\chi^0_1)$=100 GeV, $\tau$>10 ns | 1604.04520 |
| | GMSB, stable $\tilde\tau$, $\tilde\chi^0_1\to\tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$ | 1-2 $\mu$ | - | - | 19.1 | $\tilde\chi^0_1$ 537 GeV | 10<tan$\beta$<50 | 1411.6795 |
| | GMSB, $\tilde\chi^0_1\to\gamma\tilde G$, long-lived $\tilde\chi^0_1$ | 2 $\gamma$ | - | Yes | 20.3 | $\tilde\chi^0_1$ 440 GeV | 1<$\tau(\tilde\chi^0_1)$<3 ns, SPS8 model | 1409.5542 |
| | $\tilde g\tilde g$, $\tilde\chi^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$ | displ. $ee/e\mu/\mu\mu$ | - | - | 20.3 | $\tilde\chi^0_1$ 1.0 TeV | 7 <$c\tau(\tilde\chi^0_1)$< 740 mm, $m(\tilde g)$=1.3 TeV | 1504.05162 |
| | GGM $\tilde g\tilde g$, $\tilde\chi^0_1\to Z\tilde G$ | displ. vtx + jets | - | - | 20.3 | $\tilde\chi^0_1$ 1.0 TeV | 6 <$c\tau(\tilde\chi^0_1)$< 480 mm, $m(\tilde g)$=1.1 TeV | 1504.05162 |
| RPV | LFV $pp\to\tilde\nu_\tau+X$, $\tilde\nu_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu$,$e\tau$,$\mu\tau$ | - | - | 3.2 | $\tilde\nu_\tau$ 1.9 TeV | $\lambda'_{311}$=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079 |
| | Bilinear RPV CMSSM | 2 $e,\mu$ (SS) | 0-3 $b$ | Yes | 20.3 | $\tilde q,\tilde g$ 1.45 TeV | $m(\tilde q)$=$m(\tilde g)$, $c\tau_{LSP}$<1 mm | 1404.2500 |
| | $\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to W\tilde\chi^0_1$, $\tilde\chi^0_1\to ee\nu, e\mu\nu, \mu\mu\nu$ | 4 $e,\mu$ | - | Yes | 13.3 | $\tilde\chi^\pm_1$ 1.14 TeV | $m(\tilde\chi^0_1)$>400GeV, $\lambda_{12k}\neq0$ ($k$ = 1,2) | ATLAS-CONF-2016-075 |
| | $\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to W\tilde\chi^0_1$, $\tilde\chi^0_1\to\tau\tau\nu_e, e\tau\nu_\tau$ | 3 $e,\mu$ + $\tau$ | - | Yes | 20.3 | $\tilde\chi^\pm_1$ 450 GeV | $m(\tilde\chi^0_1)$>0.2×$m(\tilde\chi^\pm_1)$, $\lambda_{133}\neq0$ | 1405.5086 |
| | $\tilde g\tilde g$, $\tilde g\to qqq$ | 0 | 4-5 large-$R$ jets | - | 14.8 | $\tilde g$ 1.08 TeV | BR($t$)=BR($b$)=BR($c$)=0% | ATLAS-CONF-2016-057 |
| | $\tilde g\tilde g$, $\tilde g\to qq\tilde\chi^0_1$, $\tilde\chi^0_1\to qqq$ | 0 | 4-5 large-$R$ jets | - | 14.8 | $\tilde g$ 1.55 TeV | $m(\tilde\chi^0_1)$=800 GeV | ATLAS-CONF-2016-057 |
| | $\tilde g\tilde g$, $\tilde g\to\tilde t_1t$, $\tilde t_1\to bs$ | 2 $e,\mu$ (SS) | 0-3 $b$ | Yes | 13.2 | $\tilde g$ 1.3 TeV | $m(\tilde t_1)$<750 GeV | ATLAS-CONF-2016-037 |
| | $\tilde t_1\tilde t_1$, $\tilde t_1\to bs$ | 0 | 2 jets + 2 $b$ | Yes | 15.4 | $\tilde t_1$ 410 GeV<br>450-510 GeV | | ATLAS-CONF-2016-022, ATLAS-CONF-2016-084 |
| | $\tilde t_1\tilde t_1$, $\tilde t_1\to b\ell$ | 2 $e,\mu$ | 2 $b$ | - | 20.3 | $\tilde t_1$ 0.4-1.0 TeV | BR($\tilde t_1\to be/\mu$)>20% | ATLAS-CONF-2015-015 |
| Other | Scalar charm, $\tilde c\to c\tilde\chi^0_1$ | 0 | 2 $c$ | Yes | 20.3 | $\tilde c$ 510 GeV | $m(\tilde\chi^0_1)$<200 GeV | 1501.01325 |

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

# Searches for WIMP particles

*PRL, 116, 161301 (2016)*
*arXiv: 1608.07648*



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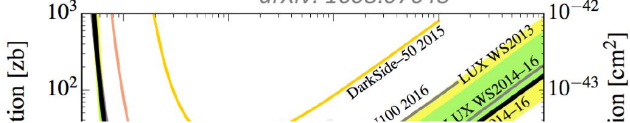
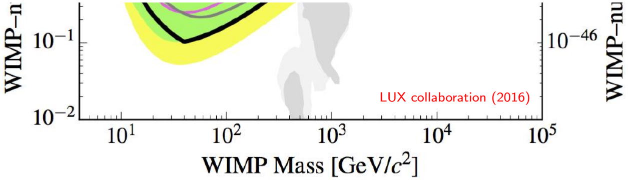


We have to look at the TeV scale!



LUX collaboration (2016)

# Multi-TeV DM scenarios

Simple assumption: extend the SM with an electroweak multiplet

| Quantum Numbers | | |
|---|---|---|
| $SU(2)_L$ | $U(1)_Y$ | Spin |
| 2 | $1/2$ | 0 |
| | $1/2$ | $1/2$ |
| 3 | 0 | 0 |
| | 0 | $1/2$ |
| | 1 | 0 |
| | 1 | $1/2$ |
| 4 | $1/2$ | 0 |
| | $1/2$ | $1/2$ |
| | $3/2$ | 0 |
| | $3/2$ | $1/2$ |
| 5 | 0 | 0 |
| | 0 | $1/2$ |
| 7 | 0 | 0 |

Cirelli, Fornengo, Strumia (2005)

# Multi-TeV DM scenarios

Simple assumption: extend the SM with an electroweak multiplet

| Quantum Numbers | | | |
|---|---|---|---|
| $SU(2)_L$ | $U(1)_Y$ | Spin | |
| 2 | 1/2 | 0 | Inert doublet model |
| | 1/2 | 1/2 | Higgsino DM |
| 3 | 0 | 0 | |
| | 0 | 1/2 | Wino DM |
| | 1 | 0 | |
| | 1 | 1/2 | |
| 4 | 1/2 | 0 | |
| | 1/2 | 1/2 | |
| | 3/2 | 0 | |
| | 3/2 | 1/2 | |
| 5 | 0 | 0 | |
| | 0 | 1/2 | Fermionic 5-plet |
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Cirelli, Fornengo, Strumia (2005)

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Cirelli, Fornengo, Strumia (2005)

Inert doublet model 0.5-20 TeV

Higgsino DM $\sim$ 1 TeV

Wino DM $\sim$ 2.9 TeV

Fermionic 5-plet $\sim$ 10 TeV

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| 4 | 3/2 | 0 | |
| | 3/2 | 1/2 | |
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| 7 | 0 | 0 | Scalar 7-plet $\sim$ 25 TeV |

Cirelli, Fornengo, Strumia (2005)

How do we test these models?
Gamma-ray telescopes

# Part I:
# Gamma-ray spectral features in indirect dark matter searches

# One example: minimal DM Scenario

$$\chi = \begin{pmatrix} \chi^{2+} \\ \chi^{+} \\ \chi^{0} \\ -\chi^{-} \\ \chi^{2-} \end{pmatrix}$$

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \frac{1}{2}\overline{\chi}\left(i\not{D} - M\right)\chi$$

Cirelli, Fornengo, Strumia (2005)

- $\chi^+$ and $\chi^0$ get a mass splitting at loop-level: $\Delta M = 166\,\mathrm{MeV}$.
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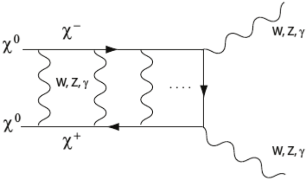

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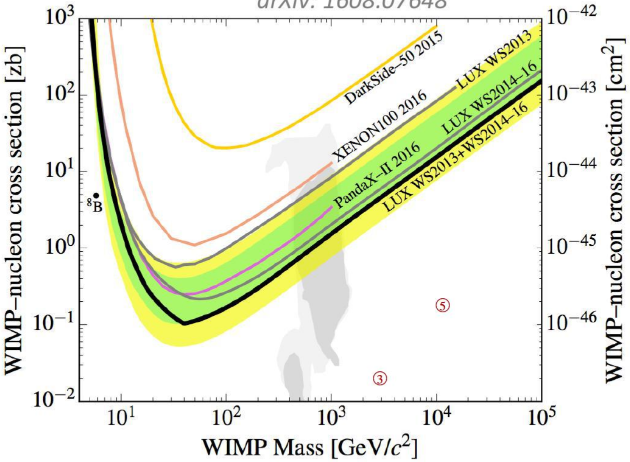
Cirelli, Fornengo, Strumia (2005)

- $\chi^+$ and $\chi^0$ get a mass splitting at loop-level: $\Delta M = 166\,\mathrm{MeV}$.
- $\chi^0$ is naturally the ligthest and automatically stable.
- Only one parameter. Very predictive scenario.
- A detailed calculation of the relic density shows that $M \approx 11.5\,\mathrm{TeV}$

Mitridate, Redi, Smirnov, Strumia (2017)

# Direct searches

PRL, 116, 161301 (2016)
arXiv: 1608.07648



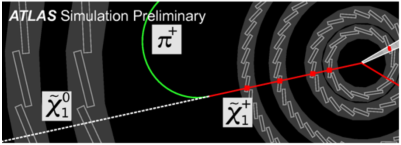
Hisano, Ishiwata, Nagata (2015)

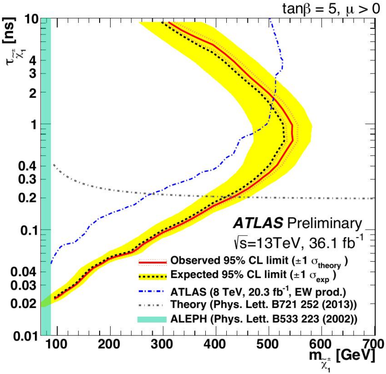
# LHC searches

Look into the channel $pp \to j\chi^\pm\chi^0$

$$\underbrace{\tilde{\chi}_1^\pm}_{\text{leave hits}} \longrightarrow \underbrace{\tilde{\chi}_1^0}_{E_T^{miss}} + \underbrace{\pi^\pm}_{\text{Undetectable}}$$

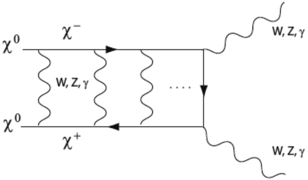
-> disappearing track



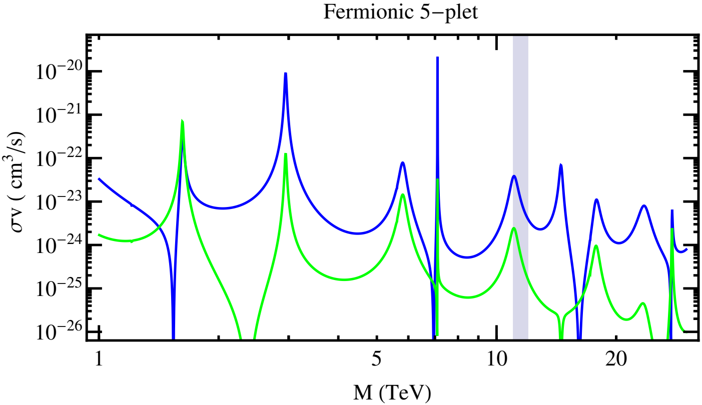


$M < 430\,\mathrm{GeV}$ are excluded. MoriondEW (2017)

# Indirect searches of the 5-plet

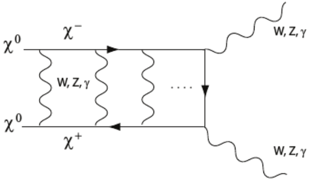


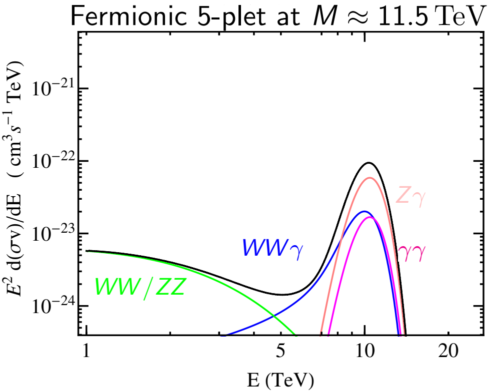
In the early Universe
$\sigma v \sim 1\,\mathrm{pb} \approx 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$.
Sommerfeld Effect



GGC, Ibarra, Lamperstorfer, Tytgat (2015)

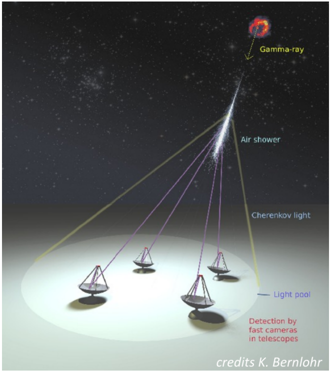
# Gamma-ray spectrum





GGC, Ibarra, Lamperstorfer, Tytgat (2015)

# The H.E.S.S. Experiment (High Energy Stereoscopic System)



*credits K. Bernlohr*

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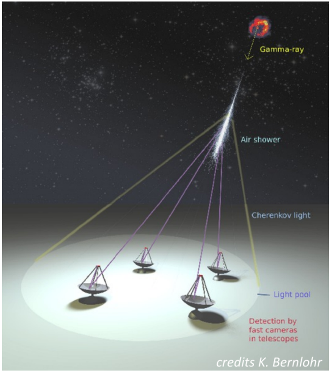
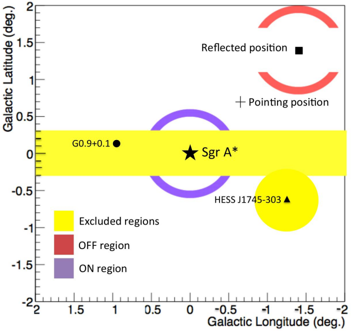
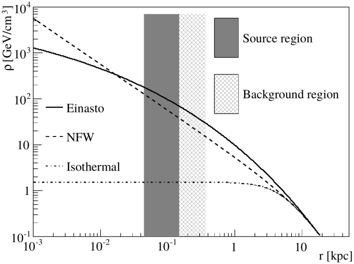


credits K. Bernlohr

Large cosmic-ray background → brightest targets are best (Galactic Center)

# H.E.S.S. searches for a continuum of photons





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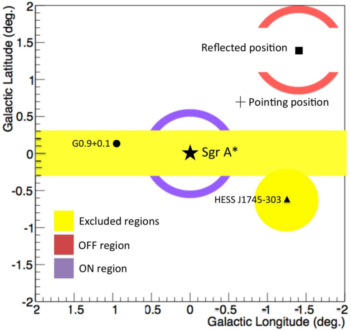
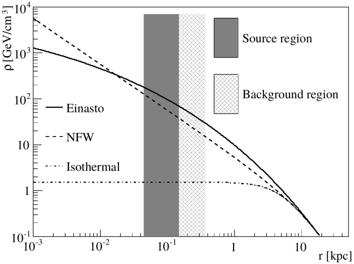
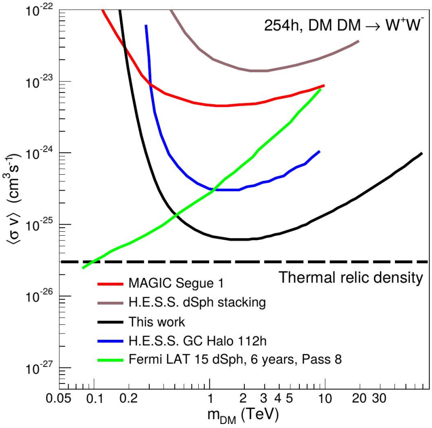
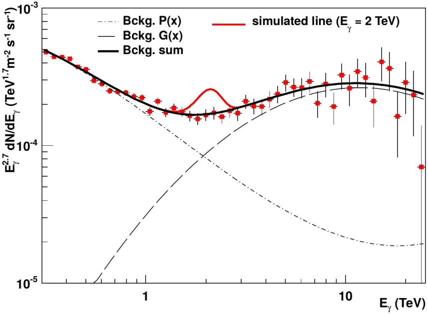


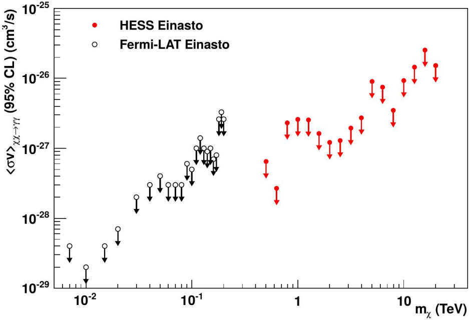


It only works for cuspy profiles!



# H.E.S.S. searches for line-like features





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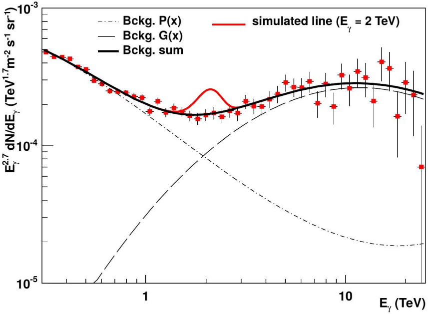
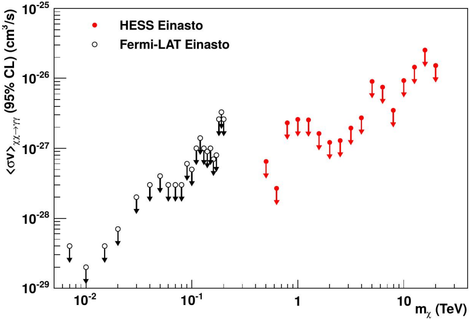
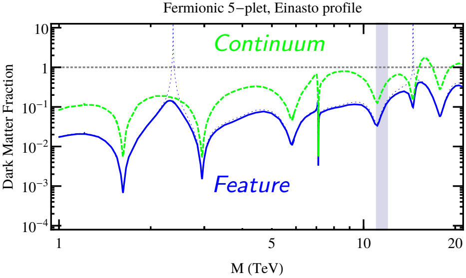
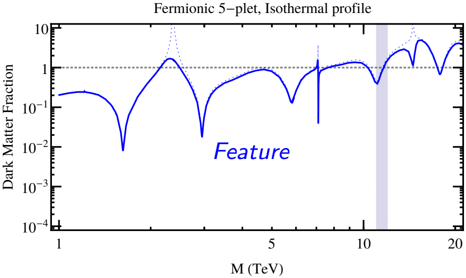




It makes use of the spectral feature and works for any profile

# H.E.S.S. Limits from the Galactic Center





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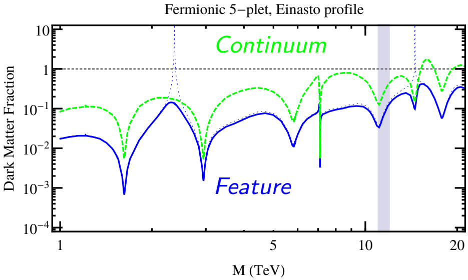

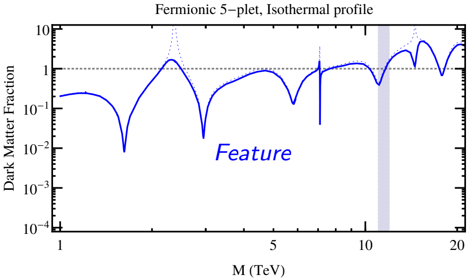

Spectral features are very important to study these models.

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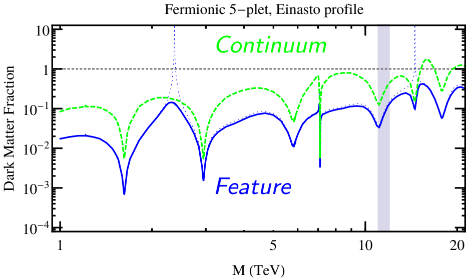
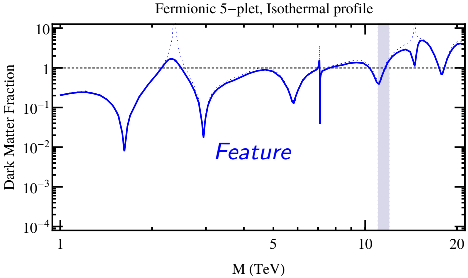




Spectral features are very important to study these models.

The 5-plet is under severe tension.

# Left-Right Symmetric DM

Extend the idea of of only multiplet but consider the group

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

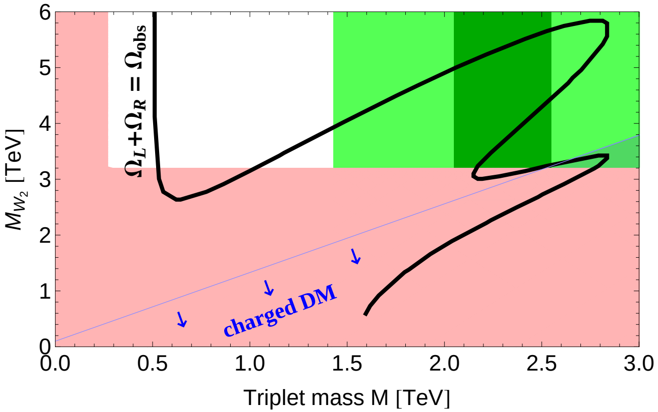
Heeck, Patra (2015)

| Fermionic Representation |
|---|
| $(\mathbf{3},\mathbf{1},0) \oplus (\mathbf{1},\mathbf{3},0)$ |
| $(\mathbf{5},\mathbf{1},0) \oplus (\mathbf{1},\mathbf{5},0)$ |
| $(\mathbf{2},\mathbf{2},0)$ |
| $(\mathbf{3},\mathbf{3},0)$ |

Only the mass is a free parameter. Stability is guaranteed by a remnant symmetry. Very predictive scenarios!

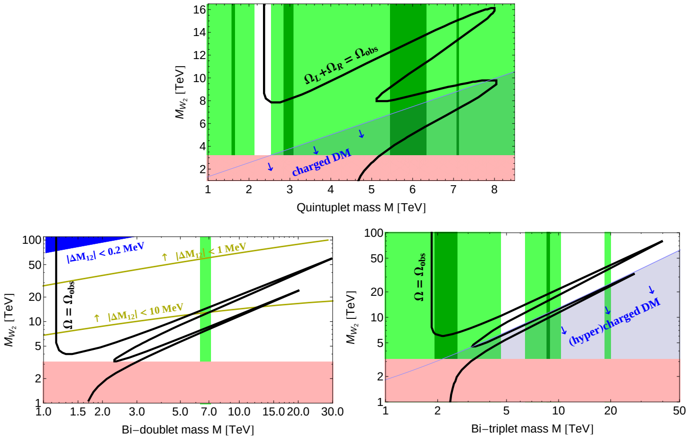
# The case of the left-right symmetric triplet

Interplay between LHC searches, mesons physics and indirect searches with lines



CGC, Heeck (2016)

# Other candidates



CGC, Heeck (2016)

# General calculation of the rates for DM DM $\rightarrow \gamma\gamma$

Journal of Cosmology and Astroparticle Physics

## General calculation of the cross section for dark matter annihilations into two photons

Camilo Garcia-Cely[a] and Andres Rivera[b,a]

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Journal of Cosmology and Astroparticle Physics, Volume 2017, March 2017

### Abstract

Assuming that the underlying model satisfies some general requirements such as renormalizability and CP conservation, we calculate the non-relativistic one-loop cross section for any self-conjugate dark matter particle annihilating into two photons. We accomplish this by carefully classifying all possible one-loop diagrams and, from them, reading off the dark matter interactions with the particles running in the loop. Our approach is general and leads to the same results found in the literature for popular dark matter candidates such as the neutralinos of the MSSM, minimal dark matter, inert Higgs and Kaluza-Klein dark matter.

# How about neutrino lines?

- Neutrinos are similar to photons. They point to the direction where they were produced.
- Neutrino lines can be easily disentangled from the astrophysical background.

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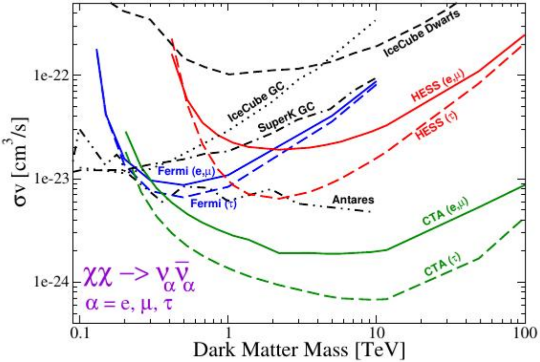

Queiroz, Yaguna, Weniger (2016)

# Part II:
# Neutrino lines in indirect dark matter searches

# Can we really get neutrino lines from annihilating DM?

- Majorana or Scalar DM → p-wave annihilations.

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- We must consider Dirac DM with no hypercharge. One example is a triplet coupled to a doublet.

./Pictures/GCF2.pdf

./Pictures/dSphF2.pdf

All this is preliminary work

# Can we really get neutrino lines from annihilating DM?

- Majorana or Scalar DM → p-wave annihilations.
- We must consider Dirac DM with no hypercharge. One example is a triplet coupled to a doublet.
- At the TeV scale, gauge invariance forces us to consider the charged lepton channels.

./Pictures/GCF2.pdf

./Pictures/dSphF2.pdf

All this is preliminary work

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- Annihilating dark matter into neutrino lines is constrained in multiple ways.
- We can give up the WIMP paradigm and consider decaying dark matter instead.

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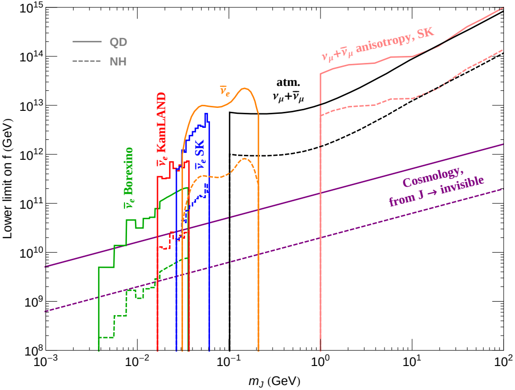
- For sufficiently a large symmetry-breaking scale, the Majoron has a lifetime larger than the age of the Universe and is therefore a DM candidate.
- Majorons decay and produce neutrino lines.

# Majoron DM



- $\nu$ lines are the most important decay channel of Majoron DM.
- Neutrino experiments can be used as DM detectors.

CGC, Heeck (2017)

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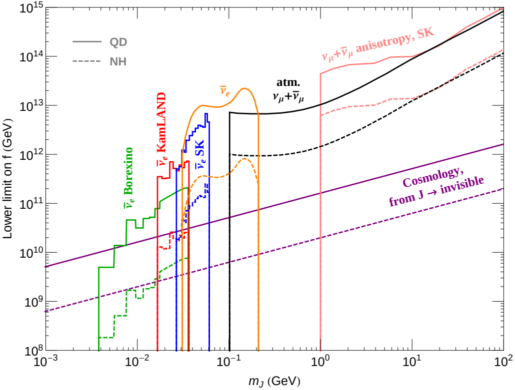

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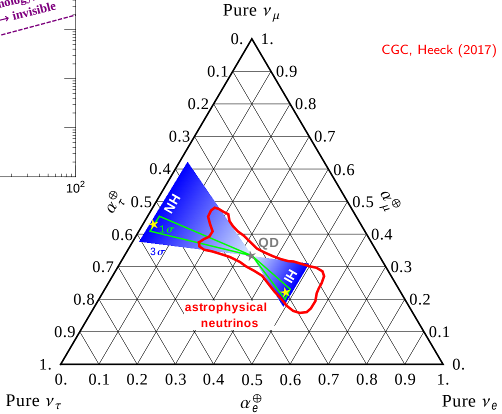
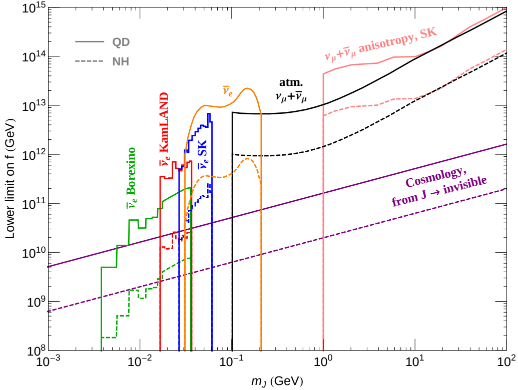


CGC, Heeck (2017)

# Majoron DM



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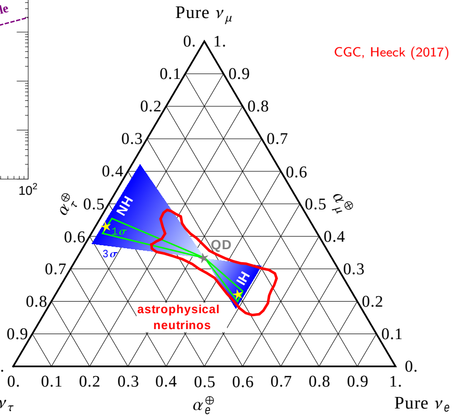
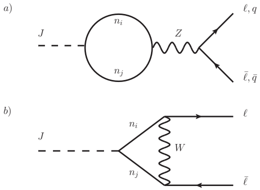
- Neutrinos also carry flavor
- Majoron DM gives rise to different flavor ratios than astrophysical processes.

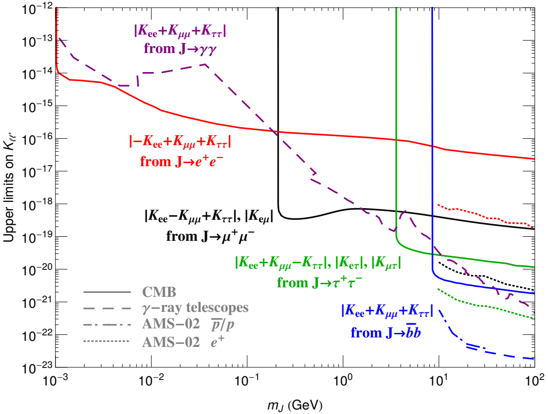


CGC, Heeck (2017)

# Charged final states

There are final states taking place at one-loop and two-loop level. They depend on different parameters. CGC, Heeck (2017)





# Conclusions

- Multi-TeV DM models predict a significant annihilation cross-sections into gamma-rays due to the Sommerfeld effect. Much above the canonical thermal value.
- The best test to them is via their annihilation into gamma-ray lines
- Neutrino lines from annihilating dark matter are also a very important channel, however they are in practice hard to obtain because of multiple constraints. Work in progress
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Thanks for your attention!