# Minimal dark matter models

with radiative neutrino masses

Michael Klasen

Institute for Theoretical Physics, University of Münster

18 September 2018

Graduiertenkolleg 2149
Research Training Group

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

# References

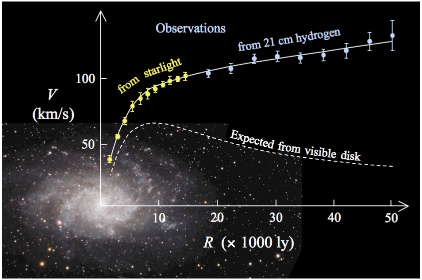
- D. Restrepo, O. Zapata, C. Yaguna
  Models with radiative neutrino masses and viable dark matter candidates
  JHEP 1311 (2013) 011 [1308.3655]

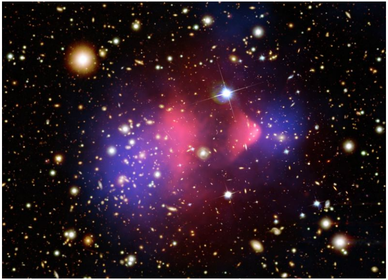
# References

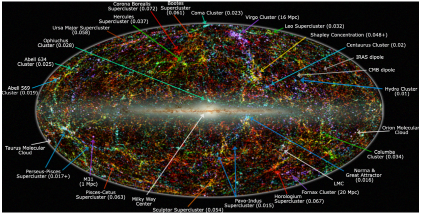
- D. Restrepo, O. Zapata, C. Yaguna
  Models with radiative neutrino masses and viable dark matter candidates
  JHEP 1311 (2013) 011 [1308.3655]
- MK, C. Yaguna, J. Ruiz-Alvarez, D. Restrepo, O. Zapata
  Scalar dark matter and fermion coannihilations in the radiative seesaw model
  JCAP 1304 (2013) 044 [1302.5298]
- S. Esch, MK, D. Lamprea, C. Yaguna
  Lepton flavor violation and scalar dark matter in a radiative model of neutrino masses
  Eur. Phys. J. C 78 (2018) 88 [1602.05137]
- S. Esch, MK, C. Yaguna
  A singlet doublet dark matter with radiative neutrino masses
  JHEP (under review) [1804.03384]

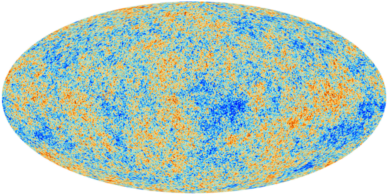
# Observational evidence for dark matter

MK, M. Pohl, G. Sigl, Prog. Nucl. Part. Phys. 85 (2015) 1 [1507.03800]



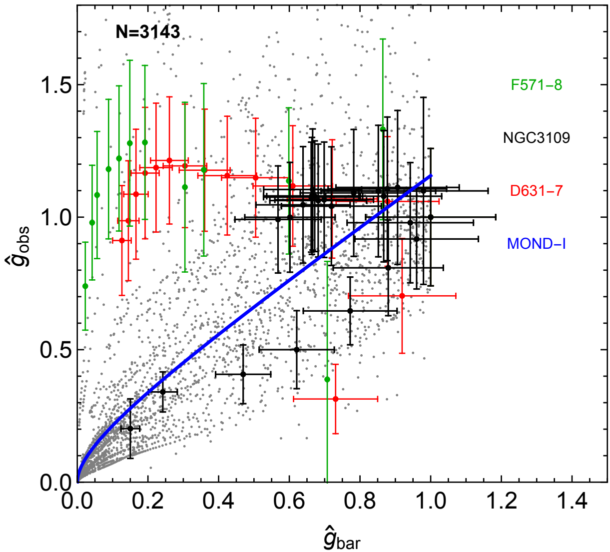





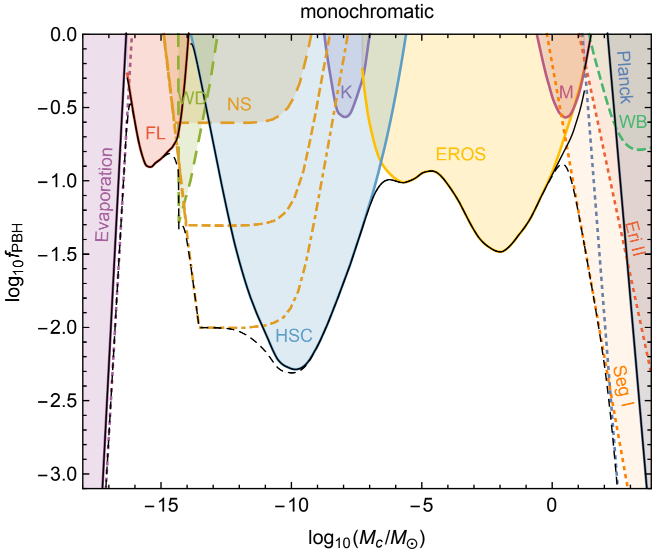
# Galactic rotation curve data and MOND

M. Frandsen, J. Petersen, 1805.10706



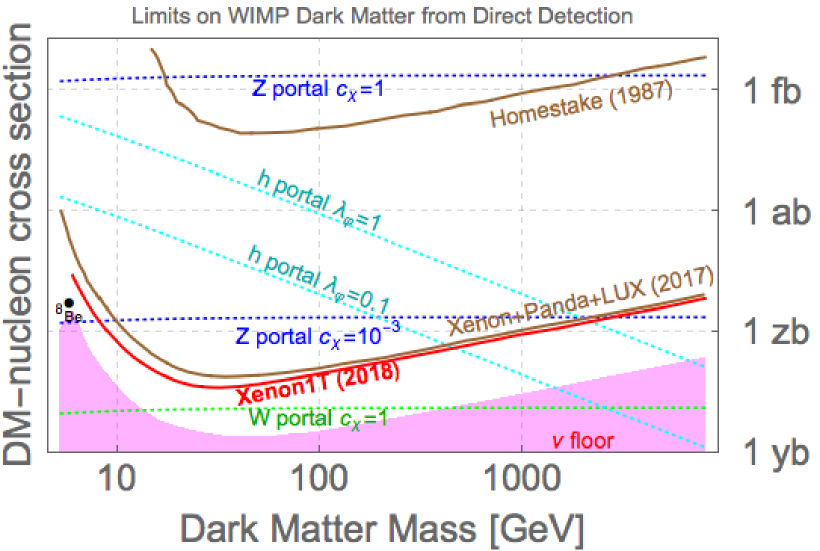
# Constraints on Primary Black Hole mass and DM fraction

B. Carr, M. Raidal, T. Tenkanen, V. Vaskonen, H. Veermäe, Phys. Rev. D96 (2017) 023514 [1705.05567]



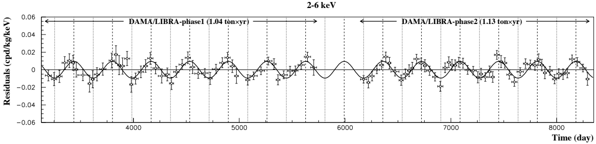
# Probing the Weakly Interacting Massive Particle paradigm

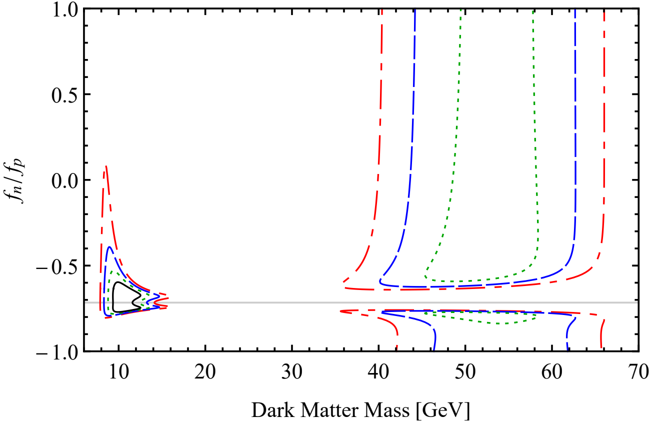
E. Aprile et al. [Xenon1T], 1805.12562



# DAMA/LIBRA-phase2 and isospin-violating DM

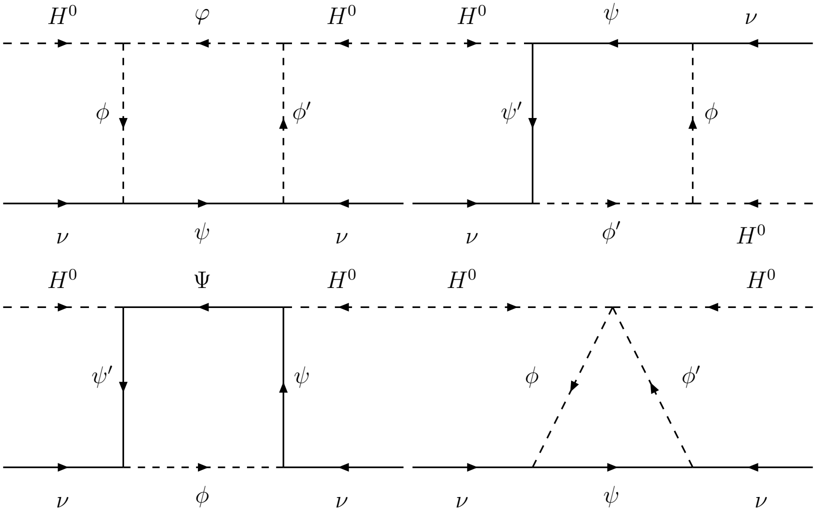
R. Bernabei et al. [DAMA/LIBRA-phase2], 1805.10486; S. Baum, K. Freese, C. Kelso, 1804.01231



# Models with radiative neutrino masses and dark matter

F. Bonnet, M. Hirsch, T. Ota, W. Winter, JHEP 1207 (2012) 153; Y. Farzan, S. Pascoli, M. Schmidt, JHEP 1303 (2013) 107; D. Restrepo, O. Zapata, C. Yaguna, JHEP 1311 (2013) 011; Y. Cai et al., Front. in Phys. 5 (2017) 63



# The best studied class: T3

Y. Farzan, S. Pascoli, M.A. Schmidt, JHEP 1010 (2010) 111; M. Aoki, S. Kanemura, K. Yagyu, Phys. Lett. B702 (2011) 355
E. Ma, Phys. Rev. D73 (2006) 077301; E. Ma, D. Suematsu, Mod. Phys. Lett. A24 (2009) 583

| Model | $\alpha$ | Fermionic | | Scalar | | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| | | DM | DD | DM | DD | | |
| T3-A | 0 | $2_1$ | × | $1_0, 3_2$ | ✓ | ✓ | 3 |
| | $-2$ | $2_{-1}$ | × | $3_0$ | ✓ | × | 3 |
| T3-B | $1, -3$ | × | × | $2_{\pm 1}$ | ✓ | ✓ | 3 |
| | $-1$ | $1_0$ | ✓ | $2_{\pm 1}$ | ✓ | × | 2 |
| T3-C | $1, -3$ | $3_{\pm 2}$ | × | $2_{\pm 1}$ | ✓ | ✓ | 3 |
| | $-1$ | $3_0$ | ✓ | $2_{\pm 1}$ | ✓ | × | 2 |
| T3-E | $0, -2$ | $2_{\pm 1}$ | × | $3_0, 3_{\pm 2}$ | ✓ | ✓ | 3 |

# The best studied class: T3

Y. Farzan, S. Pascoli, M.A. Schmidt, JHEP 1010 (2010) 111; M. Aoki, S. Kanemura, K. Yagyu, Phys. Lett. B702 (2011) 355
E. Ma, Phys. Rev. D73 (2006) 077301; E. Ma, D. Suematsu, Mod. Phys. Lett. A24 (2009) 583

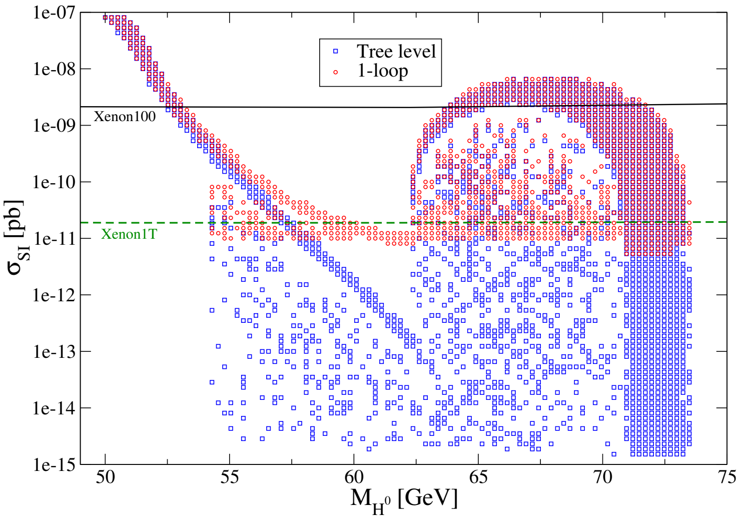
| Model | $\alpha$ | Fermionic DM | Fermionic DD | Scalar DM | Scalar DD | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| T3-A | 0 | $2_1$ | × | $1_0, 3_2$ | ✓ | ✓ | 3 |
| | $-2$ | $2_{-1}$ | × | $3_0$ | ✓ | × | 3 |
| T3-B | $1, -3$ | × | × | $2_{\pm 1}$ | ✓ | ✓ | 3 |
| | $-1$ | $1_0$ | ✓ | $2_{\pm 1}$ | ✓ | × | 2 |
| T3-C | $1, -3$ | $3_{\pm 2}$ | × | $2_{\pm 1}$ | ✓ | ✓ | 3 |
| | $-1$ | $3_0$ | ✓ | $2_{\pm 1}$ | ✓ | × | 2 |
| T3-E | $0, -2$ | $2_{\pm 1}$ | × | $3_0, 3_{\pm 2}$ | ✓ | ✓ | 3 |

Potential in T3-B with $\alpha = -1$ ("Inert Doublet Model"):

$$
\begin{aligned}
-\mathcal{L}_{H_1,H_2} &= \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 + \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 \\
&+ \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \frac{\lambda_5}{2}\left(H_1^\dagger H_2\right)^2 \\
&+ \text{h.c.}
\end{aligned}
$$

# Radiative corrections to the Inert Doublet Model

MK, J. Ruiz-Alvarez, C. Yaguna, Phys. Rev. D87 (2013) 075025 [1302.1657]



# The best studied class: T3

Y. Farzan, S. Pascoli, M.A. Schmidt, JHEP 1010 (2010) 111; M. Aoki, S. Kanemura, K. Yagyu, Phys. Lett. B702 (2011) 355
E. Ma, Phys. Rev. D73 (2006) 077301; E. Ma, D. Suematsu, Mod. Phys. Lett. A24 (2009) 583

| Model | $\alpha$ | Fermionic DM | Fermionic DD | Scalar DM | Scalar DD | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| T3-A | $0$ | $2_1$ | $\times$ | $1_0, 3_2$ | $\checkmark$ | $\checkmark$ | 3 |
| | $-2$ | $2_{-1}$ | $\times$ | $3_0$ | $\checkmark$ | $\times$ | 3 |
| T3-B | $1, -3$ | $\times$ | $\times$ | $2_{\pm1}$ | $\checkmark$ | $\checkmark$ | 3 |
| | $-1$ | $1_0$ | $\checkmark$ | $2_{\pm1}$ | $\checkmark$ | $\times$ | 2 |
| T3-C | $1, -3$ | $3_{\pm2}$ | $\times$ | $2_{\pm1}$ | $\checkmark$ | $\checkmark$ | 3 |
| | $-1$ | $3_0$ | $\checkmark$ | $2_{\pm1}$ | $\checkmark$ | $\times$ | 2 |
| T3-E | $0, -2$ | $2_{\pm1}$ | $\times$ | $3_0, 3_{\pm2}$ | $\checkmark$ | $\checkmark$ | 3 |

Potential in T3-B with $\alpha = -1$ ("Scotogenic Model"):

$$
\begin{aligned}
-\mathcal{L}_{H_1,H_2} &= \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 + \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 \\
&+ \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \frac{\lambda_5}{2}\left(H_1^\dagger H_2\right)^2 \\
&+ \text{h.c.}
\end{aligned}
$$

# The best studied class: T3

Y. Farzan, S. Pascoli, M.A. Schmidt, JHEP 1010 (2010) 111; M. Aoki, S. Kanemura, K. Yagyu, Phys. Lett. B702 (2011) 355
E. Ma, Phys. Rev. D73 (2006) 077301; E. Ma, D. Suematsu, Mod. Phys. Lett. A24 (2009) 583

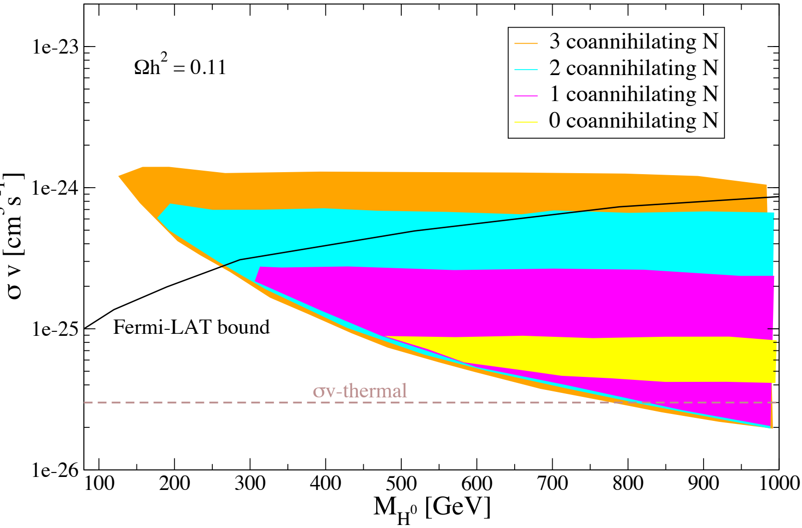
| Model | $\alpha$ | Fermionic DM | Fermionic DD | Scalar DM | Scalar DD | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| T3-A | 0 | $2_1$ | $\times$ | $1_0, 3_2$ | ✓ | ✓ | 3 |
| | $-2$ | $2_{-1}$ | $\times$ | $3_0$ | ✓ | $\times$ | 3 |
| T3-B | $1, -3$ | $\times$ | $\times$ | $2_{\pm1}$ | ✓ | ✓ | 3 |
| | $-1$ | $1_0$ | ✓ | $2_{\pm1}$ | ✓ | $\times$ | 2 |
| T3-C | $1, -3$ | $3_{\pm2}$ | $\times$ | $2_{\pm1}$ | ✓ | ✓ | 3 |
| | $-1$ | $3_0$ | ✓ | $2_{\pm1}$ | ✓ | $\times$ | 2 |
| T3-E | $0, -2$ | $2_{\pm1}$ | $\times$ | $3_0, 3_{\pm2}$ | ✓ | ✓ | 3 |

Potential in T3-B with $\alpha = -1$ ("Scotogenic Model"):

$$\begin{aligned} -\mathcal{L}_{H_1,H_2} &= \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 + \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 \\ &+ \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \frac{\lambda_5}{2}\left(H_1^\dagger H_2\right)^2 \\ &+ \text{h.c.} \\ \mathcal{L}_N &= h_{\alpha i} \bar{\ell}_\alpha H_2^\dagger P_R N_i + \text{h.c.} \end{aligned}$$

# Coannihilations in the Scotogenic Model

MK, C. Yaguna, J. Ruiz-Alvarez, D. Restrepo, O. Zapata, JCAP 1304 (2013) 044



# Class T1-3

S. Fraser, E. Ma, O. Popov, Phys. Lett. B737 (2014) 280; D. Restrepo et al., Phys. Rev. D92 (2015) 013005; S. Esch, MK, D. Lamprea, C. Yaguna, Eur. Phys. J. C78 (2018) 88; J. Fiaschi, MK, S. May, in preparation

| Model | $\alpha$ | Fermionic | | Scalar | | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| | | DM | DD | DM | DD | | |
| T1-3-A | 0 | $1_0, 2_{\pm1}$ | ✓ | $1_0$ | ✓ | × | 3 |
| T1-3-B | 0 | $1_0, 2_{\pm1}$ | ✓ | $3_0$ | ✓ | × | 3 |
| T1-3-C | $\pm1$ | $1_0, 2_{\pm1}$ | ✓ | $2_1$ | ✓ | × | 4 |
| T1-3-D | 1 | $2_1, 3_0$ | ✓ | $2_1$ | ✓ | × | 4 |
| | $-1$ | $1_0, 2_{-1}, 3_{-2}$ | ✓ | $2_{-1}$ | ✓ | ✓ | 4 |
| T1-3-F | $\pm1$ | $2_{\pm1}, 3_0, 3_{\pm2}$ | ✓ | $2_{\pm1}$ | ✓ | ✓ | 4 |
| T1-3-G | 0 | $2_{\pm1}, 3_0$ | ✓ | $1_0$ | ✓ | × | 3 |
| T1-3-H | 0 | $2_{\pm1}, 3_0$ | ✓ | $3_0$ | ✓ | × | 3 |

# Class T1-3

S. Fraser, E. Ma, O. Popov, Phys. Lett. B737 (2014) 280; D. Restrepo et al., Phys. Rev. D92 (2015) 013005; S. Esch, MK, D. Lamprea, C. Yaguna, Eur. Phys. J. C78 (2018) 88; J. Fiaschi, MK, S. May, in preparation

| Model | $\alpha$ | Fermionic DM | Fermionic DD | Scalar DM | Scalar DD | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| T1-3-A | 0 | $1_0, 2_{\pm1}$ | ✓ | $1_0$ | ✓ | × | 3 |
| T1-3-B | 0 | $1_0, 2_{\pm1}$ | ✓ | $3_0$ | ✓ | × | 3 |
| T1-3-C | $\pm1$ | $1_0, 2_{\pm1}$ | ✓ | $2_1$ | ✓ | × | 4 |
| T1-3-D | 1 | $2_1, 3_0$ | ✓ | $2_1$ | ✓ | × | 4 |
| | $-1$ | $1_0, 2_{-1}, 3_{-2}$ | ✓ | $2_{-1}$ | ✓ | ✓ | 4 |
| T1-3-F | $\pm1$ | $2_{\pm1}, 3_0, 3_{\pm2}$ | ✓ | $2_{\pm1}$ | ✓ | ✓ | 4 |
| T1-3-G | 0 | $2_{\pm1}, 3_0$ | ✓ | $1_0$ | ✓ | × | 3 |
| T1-3-H | 0 | $2_{\pm1}, 3_0$ | ✓ | $3_0$ | ✓ | × | 3 |

Potential in T1-3-B with $\alpha = 0$:

$$
\begin{aligned}
-\mathcal{L}_Y &= (\lambda_1)^{ij}(H^\dagger H)\mathrm{Tr}(\phi_i\phi_j) + (\lambda_3)^{ijkm}\mathrm{Tr}(\phi_i\phi_j\phi_k\phi_m) \\
&+ (\lambda_4(H^\dagger\psi')\Psi + \mathrm{h.c.}) + (\lambda_5(H\psi)\Psi + \mathrm{h.c.}) \\
&+ ((\lambda_6)^{ij} L_i\phi_j\psi' + \mathrm{h.c.})
\end{aligned}
$$

# Class T1-3

S. Fraser, E. Ma, O. Popov, Phys. Lett. B737 (2014) 280; D. Restrepo et al., Phys. Rev. D92 (2015) 013005;
S. Esch, MK, D. Lamprea, C. Yaguna, Eur. Phys. J. C78 (2018) 88; J. Fiaschi, MK, S. May, in preparation

| Model | $\alpha$ | Fermionic DM | Fermionic DD | Scalar DM | Scalar DD | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| T1-3-A | 0 | $1_0, 2_{\pm1}$ | ✓ | $1_0$ | ✓ | × | 3 |
| T1-3-B | 0 | $1_0, 2_{\pm1}$ | ✓ | $3_0$ | ✓ | × | 3 |
| T1-3-C | $\pm1$ | $1_0, 2_{\pm1}$ | ✓ | $2_1$ | ✓ | × | 4 |
| T1-3-D | 1 | $2_1, 3_0$ | ✓ | $2_1$ | ✓ | × | 4 |
| | $-1$ | $1_0, 2_{-1}, 3_{-2}$ | ✓ | $2_{-1}$ | ✓ | ✓ | 4 |
| T1-3-F | $\pm1$ | $2_{\pm1}, 3_0, 3_{\pm2}$ | ✓ | $2_{\pm1}$ | ✓ | ✓ | 4 |
| T1-3-G | 0 | $2_{\pm1}, 3_0$ | ✓ | $1_0$ | ✓ | × | 3 |
| T1-3-H | 0 | $2_{\pm1}, 3_0$ | ✓ | $3_0$ | ✓ | × | 3 |

Potential in T1-3-B with $\alpha = 0$:

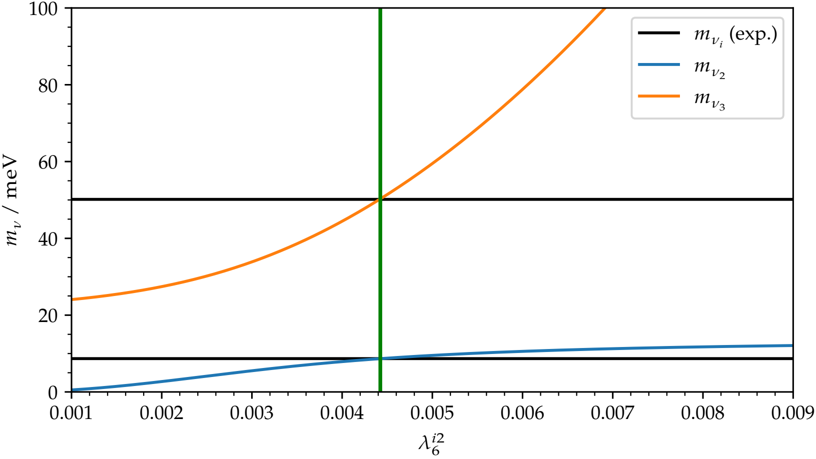
$$
\begin{aligned}
-\mathcal{L}_Y &= (\lambda_1)^{ij}(H^\dagger H)\mathrm{Tr}(\phi_i\phi_j) + (\lambda_3)^{ijkm}\mathrm{Tr}(\phi_i\phi_j\phi_k\phi_m) \\
&+ (\lambda_4(H^\dagger\psi')\Psi + \mathrm{h.c.}) + (\lambda_5(H\psi)\Psi + \mathrm{h.c.}) \\
&+ ((\lambda_6)^{ij}L_i\phi_j\psi' + \mathrm{h.c.})
\end{aligned}
$$

Neutrino mass matrix for two generations of scalars:

$$
\frac{1}{32\pi^2}\left(A_1\begin{pmatrix}(\lambda_6^{e1})^2 & \lambda_6^{e1}\lambda_6^{\mu1} & \lambda_6^{e1}\lambda_6^{\tau1}\\ \lambda_6^{\mu1}\lambda_6^{\tau1} & (\lambda_6^{\mu1})^2 & \lambda_6^{\mu1}\lambda_6^{\tau1}\\ \lambda_6^{e1}\lambda_6^{\tau1} & \lambda_6^{\mu1}\lambda_6^{\tau1} & (\lambda_6^{\tau1})^2\end{pmatrix} + A_2\begin{pmatrix}(\lambda_6^{e2})^2 & \lambda_6^{e2}\lambda_6^{\mu2} & \lambda_6^{e2}\lambda_6^{\tau2}\\ \lambda_6^{\mu2}\lambda_6^{\tau2} & (\lambda_6^{\mu2})^2 & \lambda_6^{\mu2}\lambda_6^{\tau2}\\ \lambda_6^{e2}\lambda_6^{\mu2} & \lambda_6^{\mu2}\lambda_6^{\tau2} & (\lambda_6^{\tau2})^2\end{pmatrix}\right)
$$

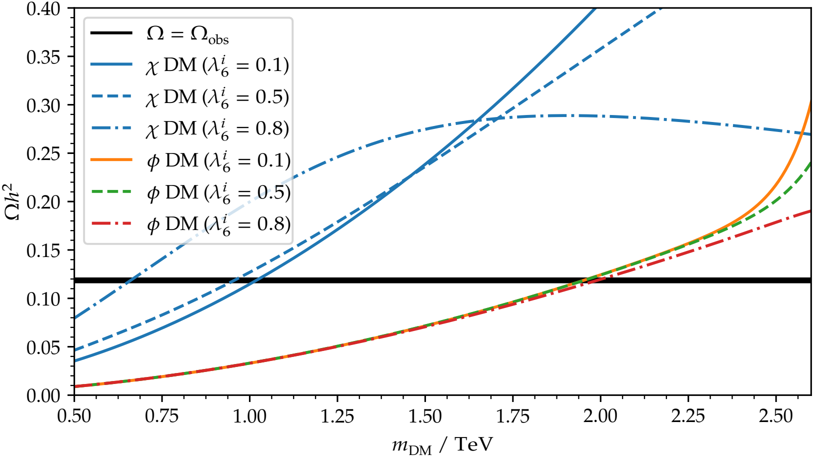
# Neutrino masses in T1-3-B

J. Fiaschi, MK, S. May, in preparation



# Relic density in T1-3-B

J. Fiaschi, MK, S. May, in preparation



# Class T1-3

S. Fraser, E. Ma, O. Popov, Phys. Lett. B737 (2014) 280; D. Restrepo et al., Phys. Rev. D92 (2015) 013005; S. Esch, MK, D. Lamprea, C. Yaguna, Eur. Phys. J. C78 (2018) 88; J. Fiaschi, MK, S. May, in preparation

| Model | $\alpha$ | Fermionic DM | Fermionic DD | Scalar DM | Scalar DD | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| T1-3-A | 0 | $1_0, 2_{\pm1}$ | ✓ | $1_0$ | ✓ | × | 3 |
| T1-3-B | 0 | $1_0, 2_{\pm1}$ | ✓ | $3_0$ | ✓ | × | 3 |
| T1-3-C | $\pm1$ | $1_0, 2_{\pm1}$ | ✓ | $2_1$ | ✓ | × | 4 |
| T1-3-D | 1 | $2_1, 3_0$ | ✓ | $2_1$ | ✓ | × | 4 |
| | $-1$ | $1_0, 2_{-1}, 3_{-2}$ | ✓ | $2_{-1}$ | ✓ | ✓ | 4 |
| T1-3-F | $\pm1$ | $2_{\pm1}, 3_0, 3_{\pm2}$ | ✓ | $2_{\pm1}$ | ✓ | ✓ | 4 |
| T1-3-G | 0 | $2_{\pm1}, 3_0$ | ✓ | $1_0$ | ✓ | × | 3 |
| T1-3-H | 0 | $2_{\pm1}, 3_0$ | ✓ | $3_0$ | ✓ | × | 3 |

Potential in T1-3-A with $\alpha = 0$:

$$\mathcal{L}_Y = \alpha_{ij}\overline{\psi'}\nu^c_{j\mathrm{L}}\phi_i + \alpha_{ij}\overline{E'}e^c_{jL}\phi_i + \frac{\beta_1}{\sqrt{2}}\overline{\psi^c}Sh + \frac{\beta_2}{\sqrt{2}}\overline{\psi'}S^c h + \mathrm{h.c.}$$

# Class T1-3

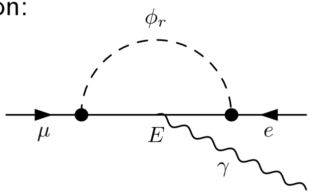
S. Fraser, E. Ma, O. Popov, Phys. Lett. B737 (2014) 280; D. Restrepo et al., Phys. Rev. D92 (2015) 013005; S. Esch, MK, D. Lamprea, C. Yaguna, Eur. Phys. J. C78 (2018) 88; J. Fiaschi, MK, S. May, in preparation

| Model | $\alpha$ | Fermionic | | Scalar | | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| | | DM | DD | DM | DD | | |
| T1-3-A | 0 | $1_0, 2_{\pm 1}$ | ✓ | $1_0$ | ✓ | × | 3 |
| T1-3-B | 0 | $1_0, 2_{\pm 1}$ | ✓ | $3_0$ | ✓ | × | 3 |
| T1-3-C | $\pm 1$ | $1_0, 2_{\pm 1}$ | ✓ | $2_1$ | ✓ | × | 4 |
| T1-3-D | 1 | $2_1, 3_0$ | ✓ | $2_1$ | ✓ | × | 4 |
| | $-1$ | $1_0, 2_{-1}, 3_{-2}$ | ✓ | $2_{-1}$ | ✓ | ✓ | 4 |
| T1-3-F | $\pm 1$ | $2_{\pm 1}, 3_0, 3_{\pm 2}$ | ✓ | $2_{\pm 1}$ | ✓ | ✓ | 4 |
| T1-3-G | 0 | $2_{\pm 1}, 3_0$ | ✓ | $1_0$ | ✓ | × | 3 |
| T1-3-H | 0 | $2_{\pm 1}, 3_0$ | ✓ | $3_0$ | ✓ | × | 3 |

Potential in T1-3-A with $\alpha = 0$:

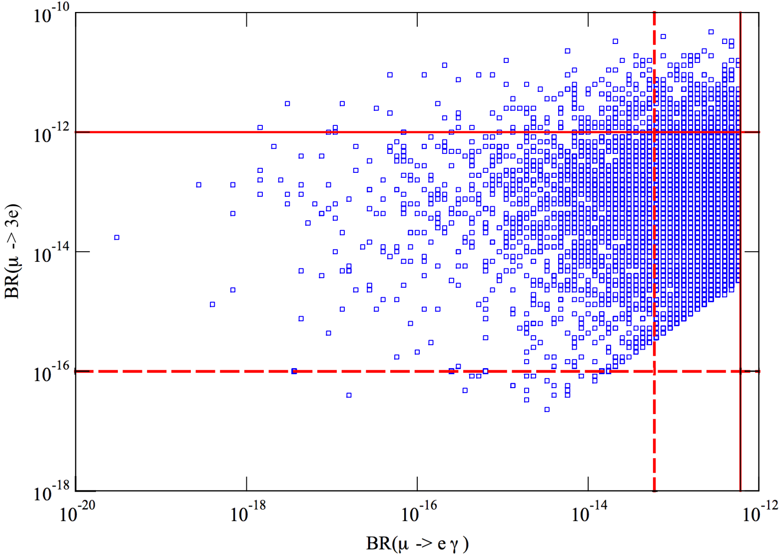
$$\mathcal{L}_Y = \alpha_{ij}\overline{\psi'}\nu^c_{j\mathrm{L}}\phi_i + \alpha_{ij}\overline{E'}e^c_{jL}\phi_i + \frac{\beta_1}{\sqrt{2}}\overline{\psi^c}Sh + \frac{\beta_2}{\sqrt{2}}\overline{\psi'}S^c h + \mathrm{h.c.}$$

Lepton flavor violation:



# Lepton flavor violation in T1-3-A

S. Esch, MK, D. Lamprea, C. Yaguna, Eur. Phys. J. C 78 (2018) 88



# Class T1-2

S. Esch, MK, C. Yaguna, 1804.03384, JHEP (under review); R. Longas, D. Portillo, D. Restrepo, O. Zapata, JHEP 1603 (2016) 162 [1511.01873]

| Model | $\alpha$ | Fermionic | | Scalar | | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| | | DM | DD | DM | DD | | |
| T1-2-A | 0 | $1_0, 2_1$ | ✓ | $1_0, 2_1$ | ✓ | × | 4 |
| | $-2$ | $2_{-1}$ | × | $2_{-1}$ | ✓ | × | 4 |
| T1-2-B | 0 | $1_0, 2_1$ | ✓ | $2_1, 3_0$ | ✓ | × | 4 |
| | $-2$ | $2_{-1}$ | × | $2_{-1}, 3_{-2}$ | ✓ | ✓ | 4 |
| T1-2-D | 1 | $2_1, 3_2$ | × | $2_1$ | ✓ | ✓ | 4 |
| | $-1$ | $2_{-1}, 3_0$ | ✓ | $1_0, 2_{-1}$ | ✓ | × | 4 |
| T1-2-F | 1 | $2_1, 3_2$ | × | $2_1, 3_2$ | ✓ | ✓ | 4 |
| | $-1$ | $2_{-1}, 3_0$ | ✓ | $2_{-1}, 3_0$ | ✓ | × | 4 |

# Class T1-2

S. Esch, MK, C. Yaguna, 1804.03384, JHEP (under review); R. Longas, D. Portillo, D. Restrepo, O. Zapata, JHEP 1603 (2016) 162 [1511.01873]

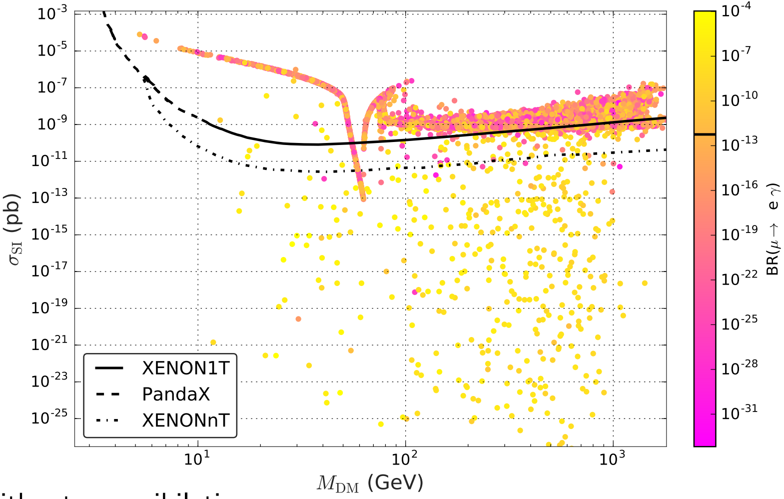
| Model | $\alpha$ | Fermionic DM | Fermionic DD | Scalar DM | Scalar DD | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| T1-2-A | 0 | $1_0, 2_1$ | ✓ | $1_0, 2_1$ | ✓ | × | 4 |
| | $-2$ | $2_{-1}$ | × | $2_{-1}$ | ✓ | × | 4 |
| T1-2-B | 0 | $1_0, 2_1$ | ✓ | $2_1, 3_0$ | ✓ | × | 4 |
| | $-2$ | $2_{-1}$ | × | $2_{-1}, 3_{-2}$ | ✓ | ✓ | 4 |
| T1-2-D | 1 | $2_1, 3_2$ | × | $2_1$ | ✓ | ✓ | 4 |
| | $-1$ | $2_{-1}, 3_0$ | ✓ | $1_0, 2_{-1}$ | ✓ | × | 4 |
| T1-2-F | 1 | $2_1, 3_2$ | × | $2_1, 3_2$ | ✓ | ✓ | 4 |
| | $-1$ | $2_{-1}, 3_0$ | ✓ | $2_{-1}, 3_0$ | ✓ | × | 4 |

Potential in T1-2-A with $\alpha = 0$:

$$
\begin{aligned}
-\mathcal{L}_{\text{scalar}} &= \frac{1}{2}\lambda_S \phi_S^2 |H|^2 + \lambda_D |\phi_D|^2 |H|^2 + \lambda_D' |\phi_D^\dagger H|^2 \\
&+ \frac{1}{2}\lambda_D'' \left[ \left(\phi_D^\dagger H\right)^2 + \text{h.c.} \right] + A \left[ \phi_D^\dagger H \phi_S + \text{h.c.} \right] \\
-\mathcal{L}_{\text{fermion}} &= y_1 \psi_{D_1} H \psi_S + y_2 \psi_{D_2} H^\dagger \psi_S + \text{h.c.} \\
-\mathcal{L}_{\text{lepton}} &= g_{1i} L_i \phi_S \psi_{D_2} + g_{2i} L_i \phi_D \psi_S + \text{h.c.}
\end{aligned}
$$

# Direct detection and lepton flavor violation in T1-2-A

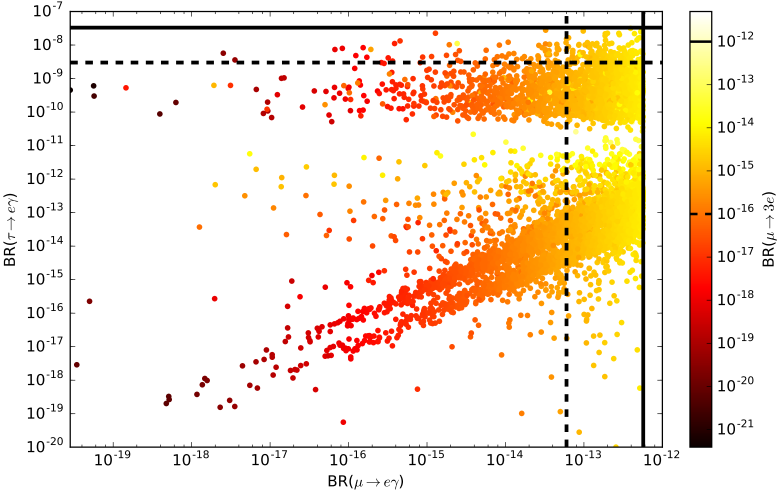
S. Esch, MK, C. Yaguna, 1804.03384, JHEP (under review)




Without coannihilation.

# Direct detection and lepton flavor violation in T1-2-A

S. Esch, MK, C. Yaguna, 1804.03384, JHEP (under review)




With coannihilation.

# Class T1-1

C. Boehm, Y. Farzan, T. Hambye, S. Palomares-Ruiz, S Pascoli, Phys. Rev. D77 (2008) 043516;
Y. Farzan, Phys. Rev. D 80 (2009) 073009

| Model | $\alpha$ | Fermionic | | Scalar | | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| | | DM | DD | DM | DD | | |
| T1-1-A | $\pm2$ | $\times$ | $\times$ | $2_{\pm1}$ | $\checkmark$ | $\checkmark$ | 4 |
| | 0 | $1_0$ | $\checkmark$ | $1_0, 2_{\pm1}$ | $\checkmark$ | $\times$ | 3 |
| T1-1-B | $\pm2$ | $3_{\pm2}$ | $\times$ | $2_{\pm1}$ | $\checkmark$ | $\checkmark$ | 4 |
| | 0 | $3_0$ | $\checkmark$ | $1_0, 2_{\pm1}$ | $\checkmark$ | $\times$ | 3 |
| T1-1-C | $\pm1$ | $2_{\pm1}$ | $\times$ | $1_0, 2_{\pm1}$ | $\checkmark$ | $\checkmark$ | 4 |
| T1-1-D | 1 | $2_1$ | $\times$ | $1_0, 2_1, 3_2$ | $\checkmark$ | $\checkmark$ | 4 |
| | $-1$ | $2_{-1}$ | $\times$ | $2_{-1}, 3_0$ | $\checkmark$ | $\times$ | 4 |
| T1-1-F | $\pm1$ | $2_{\pm1}$ | $\times$ | $2_{\pm1}, 3_0, 3_{\pm2}$ | $\checkmark$ | $\checkmark$ | 4 |
| T1-1-G | $\pm2$ | $\times$ | $\times$ | $2_{\pm1}, 3_{\pm2}$ | $\checkmark$ | $\checkmark$ | 4 |
| | 0 | $1_0$ | $\checkmark$ | $2_{\pm1}, 3_0$ | $\checkmark$ | $\times$ | 3 |
| T1-1-H | $\pm2$ | $3_{\pm2}$ | $\times$ | $2_{\pm1}, 3_{\pm2}$ | $\checkmark$ | $\checkmark$ | 4 |
| | 0 | $3_0$ | $\checkmark$ | $2_{\pm1}, 3_0$ | $\checkmark$ | $\times$ | 3 |

# Class T1-1

C. Boehm, Y. Farzan, T. Hambye, S. Palomares-Ruiz, S Pascoli, Phys. Rev. D77 (2008) 043516;
Y. Farzan, Phys. Rev. D 80 (2009) 073009

| Model | $\alpha$ | Fermionic DM | Fermionic DD | Scalar DM | Scalar DD | Exotic charges | # of N'plets |
|---|---|---|---|---|---|---|---|
| T1-1-A | $\pm 2$ | $\times$ | $\times$ | $2_{\pm 1}$ | ✓ | ✓ | 4 |
| | 0 | $1_0$ | ✓ | $1_0, 2_{\pm 1}$ | ✓ | $\times$ | 3 |
| T1-1-B | $\pm 2$ | $3_{\pm 2}$ | $\times$ | $2_{\pm 1}$ | ✓ | ✓ | 4 |
| | 0 | $3_0$ | ✓ | $1_0, 2_{\pm 1}$ | ✓ | $\times$ | 3 |
| T1-1-C | $\pm 1$ | $2_{\pm 1}$ | $\times$ | $1_0, 2_{\pm 1}$ | ✓ | ✓ | 4 |
| T1-1-D | 1 | $2_1$ | $\times$ | $1_0, 2_1, 3_2$ | ✓ | ✓ | 4 |
| | $-1$ | $2_{-1}$ | $\times$ | $2_{-1}, 3_0$ | ✓ | $\times$ | 4 |
| T1-1-F | $\pm 1$ | $2_{\pm 1}$ | $\times$ | $2_{\pm 1}, 3_0, 3_{\pm 2}$ | ✓ | ✓ | 4 |
| T1-1-G | $\pm 2$ | $\times$ | $\times$ | $2_{\pm 1}, 3_{\pm 2}$ | ✓ | ✓ | 4 |
| | 0 | $1_0$ | ✓ | $2_{\pm 1}, 3_0$ | ✓ | $\times$ | 3 |
| T1-1-H | $\pm 2$ | $3_{\pm 2}$ | $\times$ | $2_{\pm 1}, 3_{\pm 2}$ | ✓ | ✓ | 4 |
| | 0 | $3_0$ | ✓ | $2_{\pm 1}, 3_0$ | ✓ | $\times$ | 3 |

Potential in T1-1-A with $\alpha = 0$ ("SLIM Model"):

$$\begin{aligned} -\mathcal{L} &= \lambda_1 |H^T(i\sigma_2)\Phi|^2 + \mathrm{Re}[\lambda_2(H^T(i\sigma_2)\phi)^2] + \lambda_3\eta^2 H^\dagger H \\ &+ \lambda_4 \Phi^\dagger\Phi H^\dagger H + \frac{\lambda_1'}{2}(\Phi^\dagger\Phi)^2 + \frac{\lambda_2'}{2}\eta^4 + \lambda_3'\eta^2\Phi^\dagger\Phi \\ &+ g_{i\alpha}\bar{N}_i\Phi^\dagger L_\alpha \end{aligned}$$

# Scalar as LIght as MeV - solution to missing satellites?

Y. Farzan, Phys. Rev. D 80 (2009) 073009; A. Arhrib, C. Boehm, E. Ma, T.C. Yuan, JCAP 1604 (2016) 049

Constraints (scalar or fermion DM):

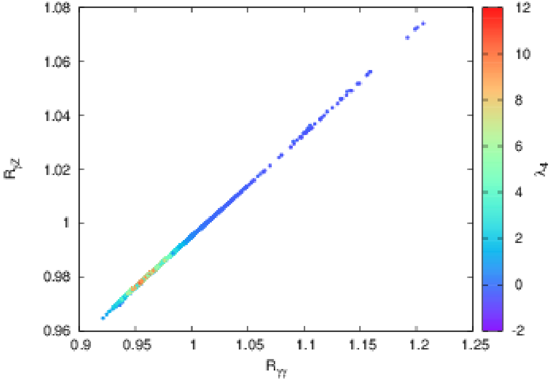
- Unitarity, vacuum stability, non-tachyonic masses
- LEP invisible $Z$ decay, $\Delta S$ and $\Delta T$; LHC $H$ decay

# Scalar as LIght as MeV - solution to missing satellites?

Y. Farzan, Phys. Rev. D 80 (2009) 073009; A. Arhrib, C. Boehm, E. Ma, T.C. Yuan, JCAP 1604 (2016) 049

Constraints (scalar or fermion DM):

- Unitarity, vacuum stability, non-tachyonic masses
- LEP invisible $Z$ decay, $\Delta S$ and $\Delta T$; LHC $H$ decay

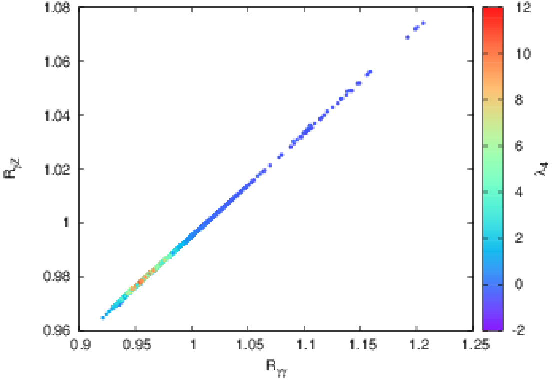


# Scalar as LIght as MeV - solution to missing satellites?

Y. Farzan, Phys. Rev. D 80 (2009) 073009; A. Arhrib, C. Boehm, E. Ma, T.C. Yuan, JCAP 1604 (2016) 049

Constraints (scalar or fermion DM):

- Unitarity, vacuum stability, non-tachyonic masses
- LEP invisible $Z$ decay, $\Delta S$ and $\Delta T$; LHC $H$ decay




ATLAS (ICHEP 2018): $R_{\gamma\gamma} = 1.08 \pm 0.08$, $R_{\gamma Z} = 2.7^{+4.6}_{-4.5} < 6.6$

# Models allowing for gauge coupling unification

C. Hagedorn, T. Ohlsson, S. Riad, M.A. Schmidt, JHEP 1609 (2016) 111 [1605.03986]

| Model | $m$ | P1 | P2 | P3 | P4 | $\Lambda$ (GeV) | $\alpha^{-1}(\Lambda)$ | $\frac{\Delta\log_{10}(\Lambda)}{\log_{10}(\Lambda)}$ (%) | $\frac{\Delta\alpha^{-1}}{\alpha^{-1}}$ (%) |
|---|---|---|---|---|---|---|---|---|---|
| T1-1-D | $1$ | $(1,2,\frac{1}{2})_S$ | $(1,1,0)_S$ | $(1,2,\frac{1}{2})_F$ | $(1,3,1)_S$ | $1.3\cdot10^{13}$ | 38.4 | 7.7 | 3.9 |
| | $-1$ | $(1,2,-\frac{1}{2})_S$ | $(1,1,-1)_S$ | $(1,2,-\frac{1}{2})_F$ | $(1,3,0)_S$ | $3.1\cdot10^{13}$ | 38.2 | 3.2 | 1.7 |
| T1-2-A | $0$ | $(1,1,0)_F$ | $(1,2,\frac{1}{2})_S$ | $(1,1,0)_S$ | $(1,2,\frac{1}{2})_F$ | $5.3\cdot10^{13}$ | 39.4 | 4.1 | 2.9 |
| T1-2-B | $0$ | $(1,1,0)_F$ | $(1,2,\frac{1}{2})_S$ | $(1,3,0)_S$ | $(1,2,\frac{1}{2})_F$ | $4.6\cdot10^{13}$ | 38.4 | 5.6 | 2.9 |
| | $-2$ | $(1,1,-1)_F$ | $(1,2,-\frac{1}{2})_S$ | $(1,3,-1)_S$ | $(1,2,-\frac{1}{2})_F$ | $3.2\cdot10^{12}$ | 35.9 | 0.54 | 0.28 |
| T1-3-A | $0$ | $(1,1,0)_F$ | $(1,2,\frac{1}{2})_F$ | $(1,1,0)_S$ | $(1,2,-\frac{1}{2})_F$ | $2.8\cdot10^{13}$ | 37.7 | 6.5 | 3.3 |
| T3-A | $0$ | $(1,1,0)_S$ | $(1,3,1)_S$ | $(1,2,\frac{1}{2})_F$ | - | $1.6\cdot10^{13}$ | 37.3 | 4.4 | 2.3 |
| | $-2$ | $(1,1,-1)_S$ | $(1,3,0)_S$ | $(1,2,-\frac{1}{2})_F$ | - | $4.0\cdot10^{13}$ | 38.7 | 0.21 | 0.11 |
| T1-3-A | $0$ | $(1,1,0)_F$ | $(1,2,\frac{1}{2})_F$ | $2\ (1,1,0)_S$ | - | $6.9\cdot10^{13}$ | 39.8 | 7.4 | 4.0 |
| T1-3-B | $0$ | $(1,1,0)_F$ | $(1,2,\frac{1}{2})_F$ | $2\ (1,3,0)_S$ | - | $5.7\cdot10^{13}$ | 38.9 | 2.5 | 1.3 |

# Conclusion

Minimal dark matter models:

- Bottum-up, small parameter space, often completely testable
- Best motivated, if they solve also other SM problems
- Intriguing: Connection to Higgs, neutrino masses, unification

# Conclusion

Minimal dark matter models:

- Bottum-up, small parameter space, often completely testable
- Best motivated, if they solve also other SM problems
- Intriguing: Connection to Higgs, neutrino masses, unification
- Many models (here only 1-loop), larger parameter spaces
- Coannihilation decouples relic density from direct detection
- Lepton flavor violation provides crucial tests

# Conclusion

Minimal dark matter models:

- Bottum-up, small parameter space, often completely testable
- Best motivated, if they solve also other SM problems
- Intriguing: Connection to Higgs, neutrino masses, unification
- Many models (here only 1-loop), larger parameter spaces
- Coannihilation decouples relic density from direct detection
- Lepton flavor violation provides crucial tests
- Many other constraints (indirect detection, LHC)
- Work in progress ...