

Neutrino masses  
dark matter and  
lepton flavor violation

Sonja Esch



With Prof. Dr. M. Klasen and Dr. C. Yaguna

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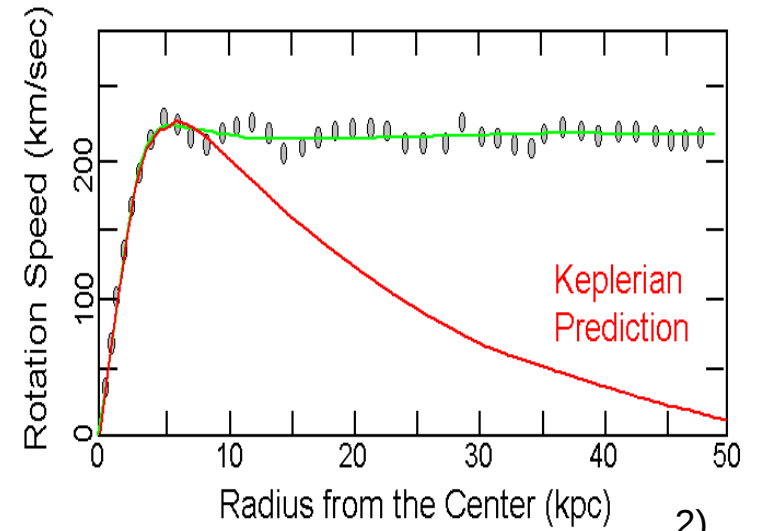
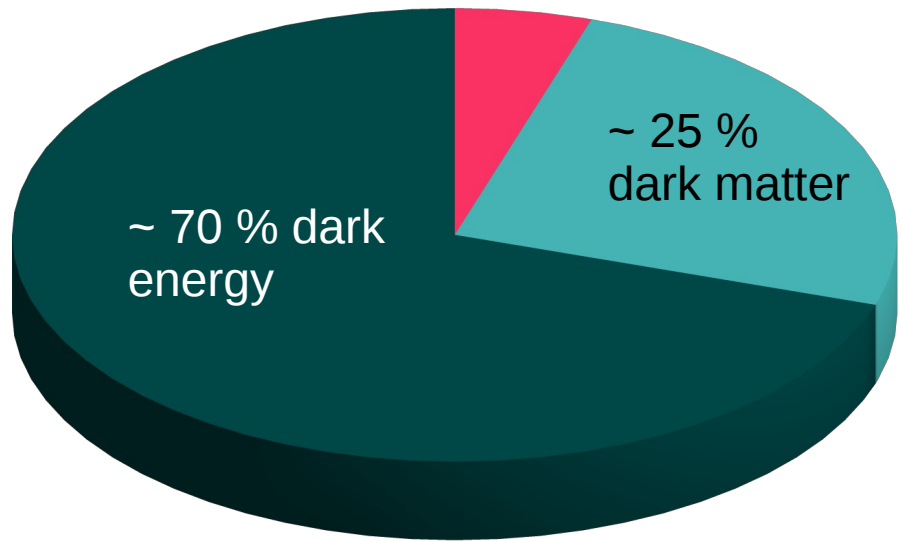
Standard Model

$\nu$   
masses

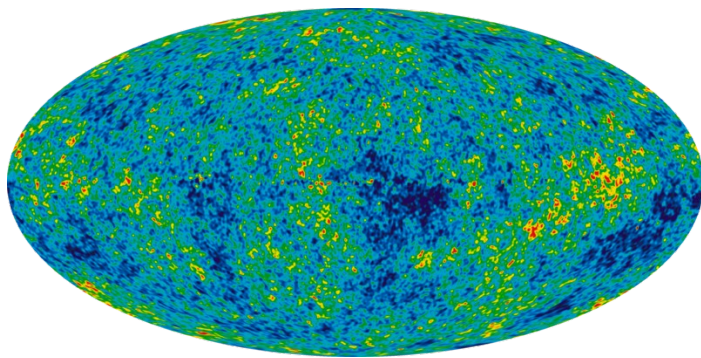
Standard Model

dark  
matter

# Dark matter evidence



Galactic rotation 2)



CMB anisotropy 1)



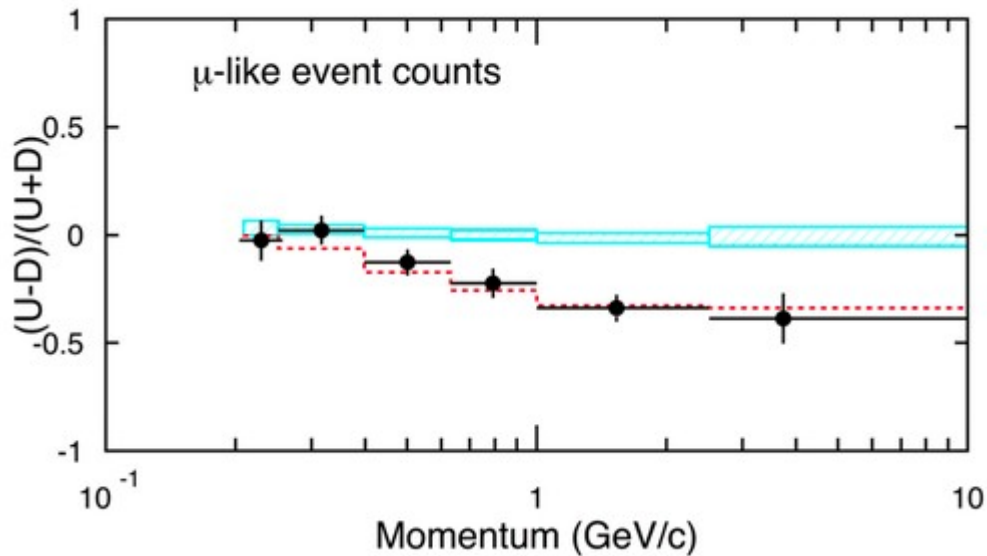
Gravitational lensing 3) 4)

# Neutrino mass evidence

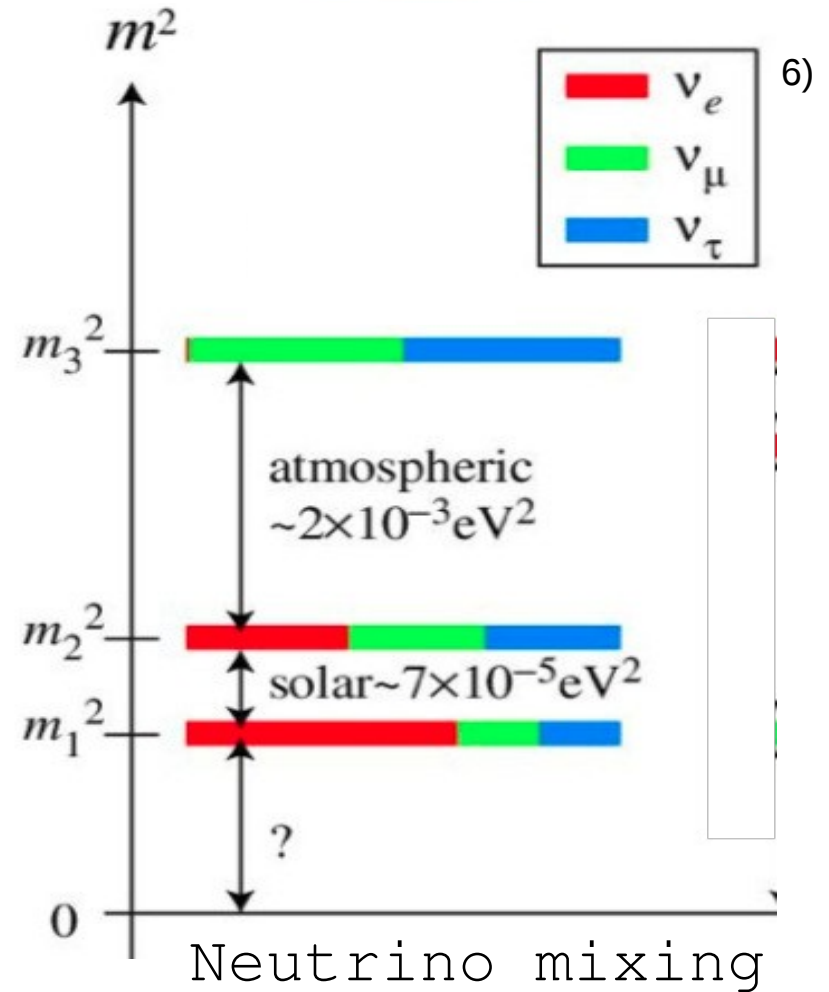
Observation of neutrino oscillation implies  $m_\nu \neq 0$



5)



Neutrino conversion 4)  
@ SuperKamiokande



5

# T12A - Neutrino masses and dark matter

D.Restrepo, O.Zapata, C.Yaguna - JHEP11(2013)

Standard Model

+

Fermion Doublet  $\psi_D$   
Fermion Singlet  $\psi_S$

+

Scalar Doublet  $\phi_D$   
Scalar Singlet  $\phi_S$

+

Extra  $Z_2$  symmetry

Dark Matter  
+  
Neutrino Masses  
+  
Lepton flavor  
violation

# T12A - Neutrino masses and dark matter

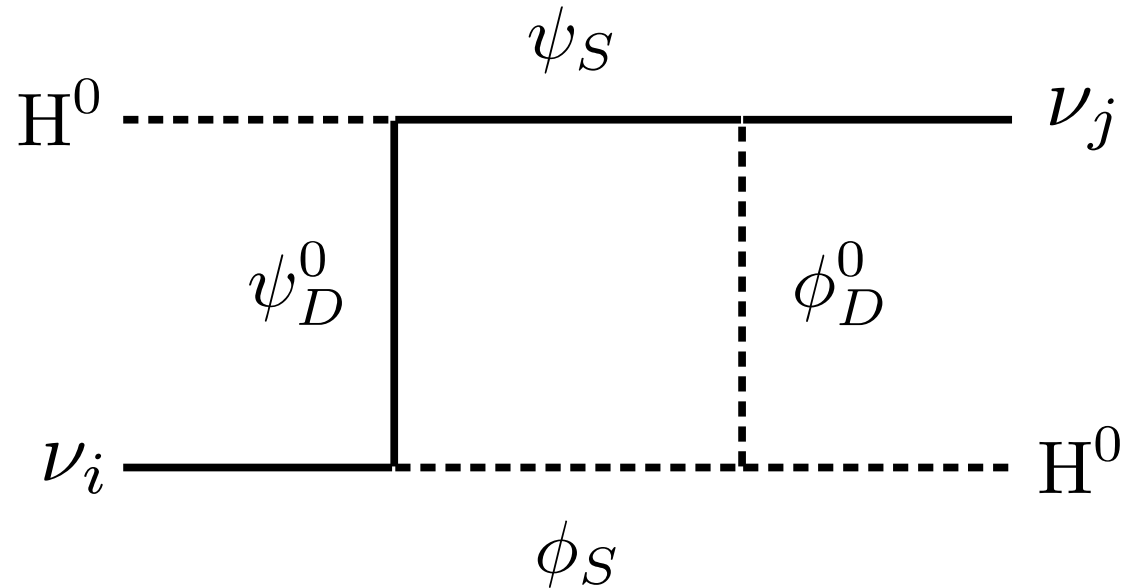
D. Restrepo, O. Zapata, C. Yaguna - JHEP11(2013)

Additional  
particles

Fermions:  
singlet  $\psi_S$   
doublet  $\psi_D$

Scalars:  
singlet  $\phi_S$   
doublet  $\phi_D$

Additional  $Z_2$   
symmetry



- Majorana neutrino masses
- Neutrino mixing

# T12A - Neutrino masses and dark matter

## Scalar SD-DM

Particles

Scalar doublet  $\phi_D$

Scalar singlet  $\phi_S$

## Fermion SD-DM

Particles

Scalar doublet  $\psi_D$

Scalar singlet  $\psi_S$

EWSB: Mixing

Mass eigenstates

3 neutral scalars

1 charged scalar

Mass eigenstates

3 neutral fermions

1 charged fermion

Dark Matter candidate

Lightest neutral  
state

Dark Matter candidate

Lightest neutral  
state

Neutrino Masses



# T12A - Neutrino masses and dark matter

## Scalar SD-DM

Particles

Scalar doublet  $\phi_D$

Scalar singlet  $\phi_S$

Mass eigenstates

3 neutral scalars

1 charged scalar

Dark Matter candidate

Lightest neutral  
state

## Fermion SD-DM

Particles

Scalar doublet  $\psi_D$

Scalar singlet  $\psi_S$

Mass eigenstates

3 neutral fermions

1 charged fermion

Dark Matter candidate

Lightest neutral  
state

# Scalar singlet doublet dark matter

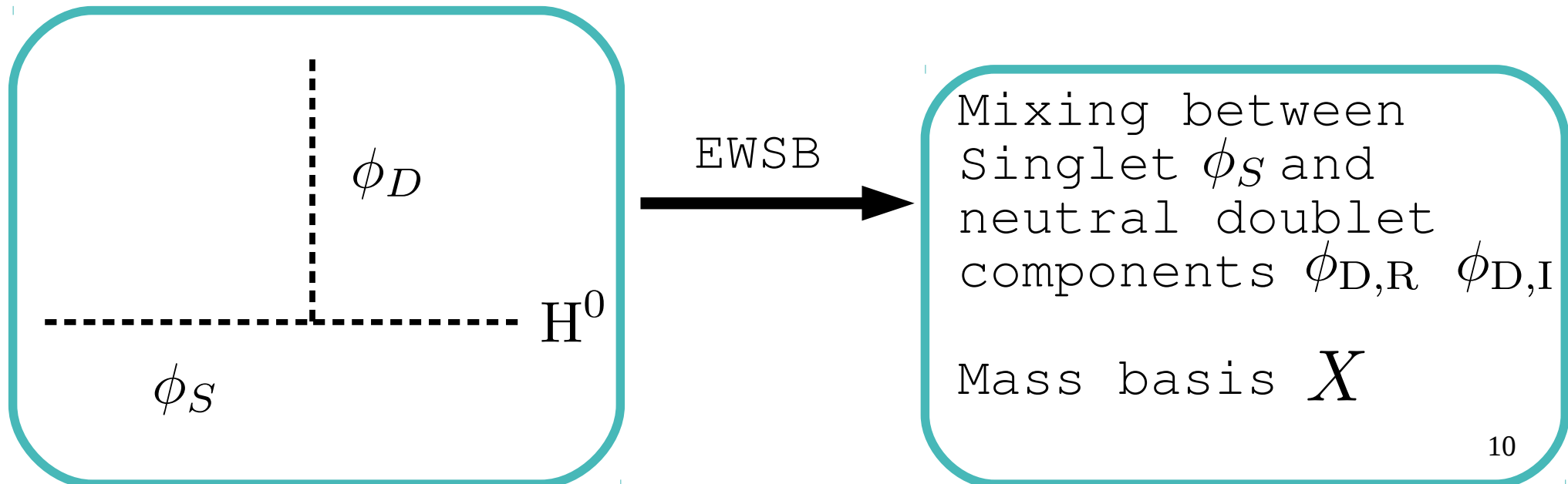
C.Cheung, D.Sanford - JCAP 02(2014)

Scalar doublet

$$\phi_D = \begin{pmatrix} \phi^- \\ \phi_{D,R} + i\phi_{D,I} \end{pmatrix}$$

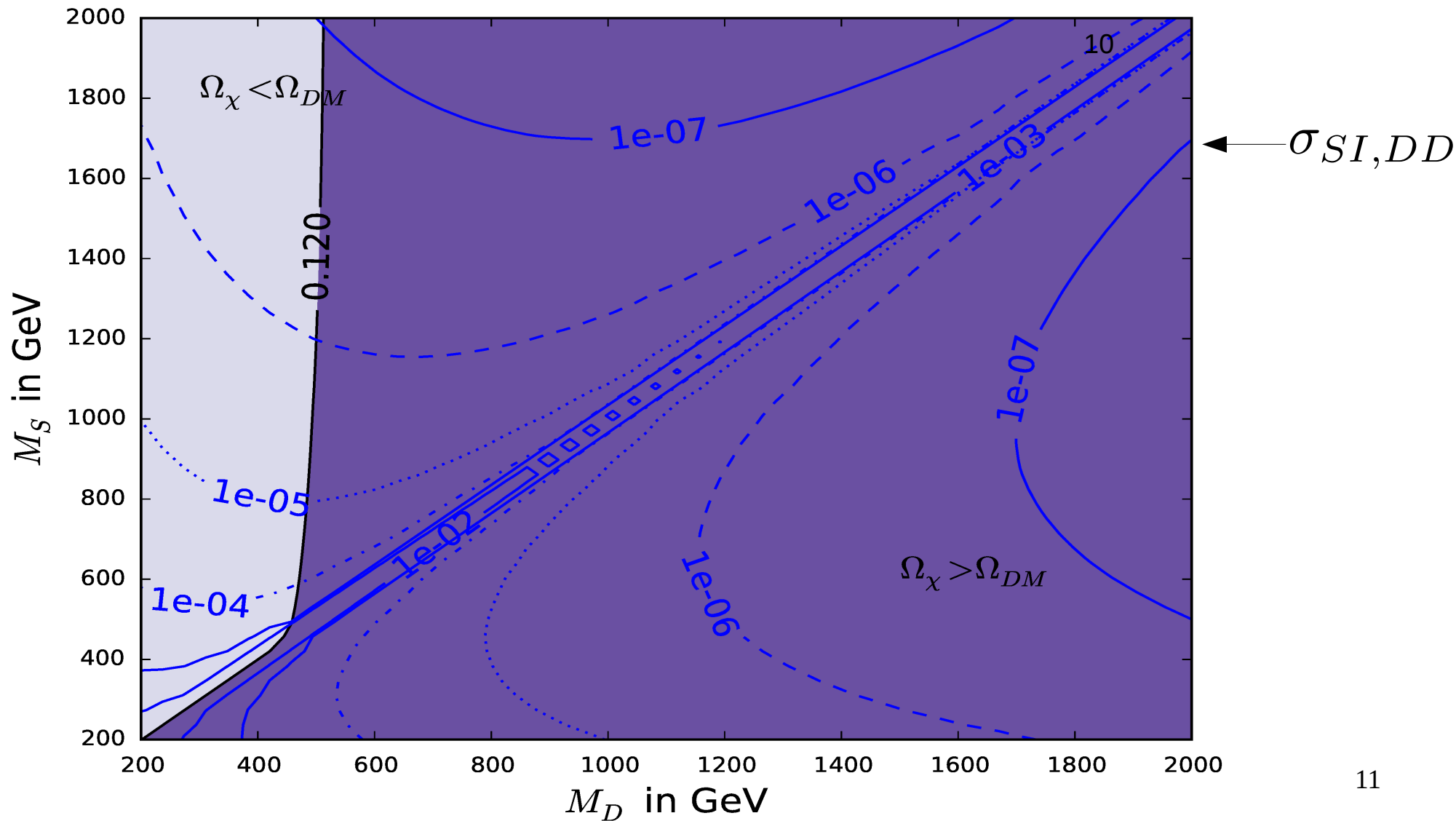
Mixing term

$$\Lambda(\phi_S H \bar{\phi}_D + \text{h.c.})$$



# Singlet doublet scalar dark matter

Lightest mass eigenstate  $X_i$  : dark matter



# T12A - Neutrino masses and dark matter

## Scalar SD-DM

Particles

Scalar doublet  $\phi_D$

Scalar singlet  $\phi_S$

Mass eigenstates

3 neutral scalars

1 charged scalar

Dark Matter candidate

Lightest neutral  
state

## Fermion SD-DM

Particles

Scalar doublet  $\psi_D$

Scalar singlet  $\psi_S$

Mass eigenstates

3 neutral fermions

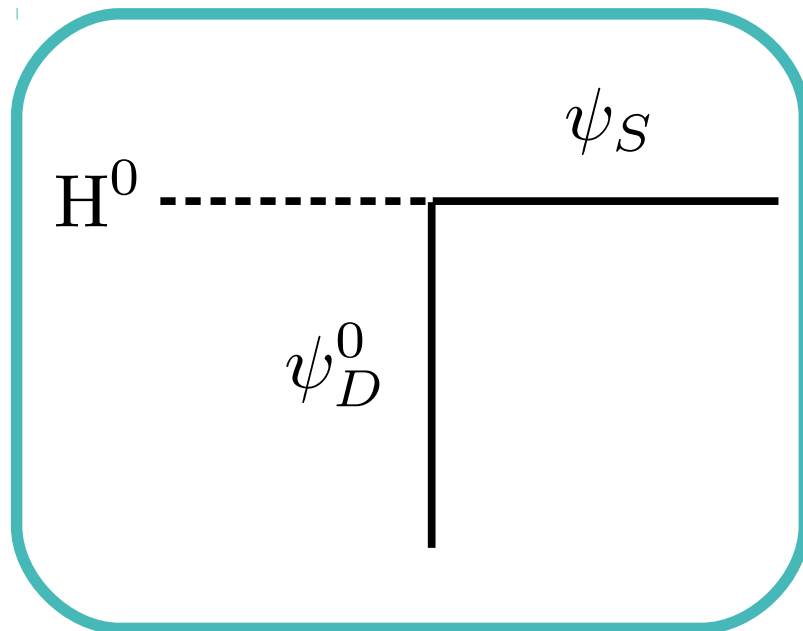
1 charged fermion

Dark Matter candidate

Lightest neutral  
state

# Fermion singlet doublet dark matter

C.Cheung, D.Sanford - JCAP 02(2014)



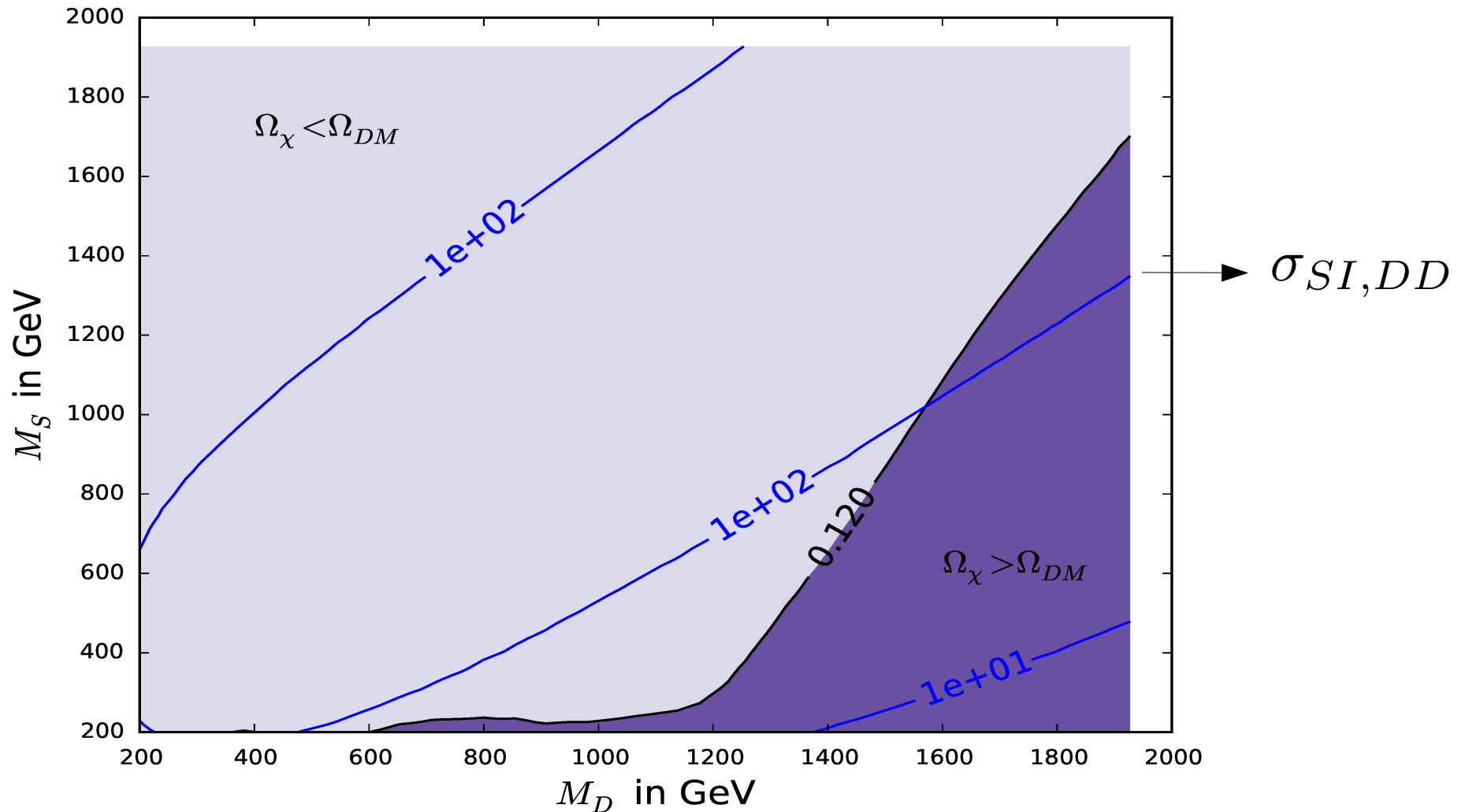
Fermion doublet

$$\psi_D = \begin{pmatrix} \psi_D^- \\ \psi_D^0 \end{pmatrix}$$

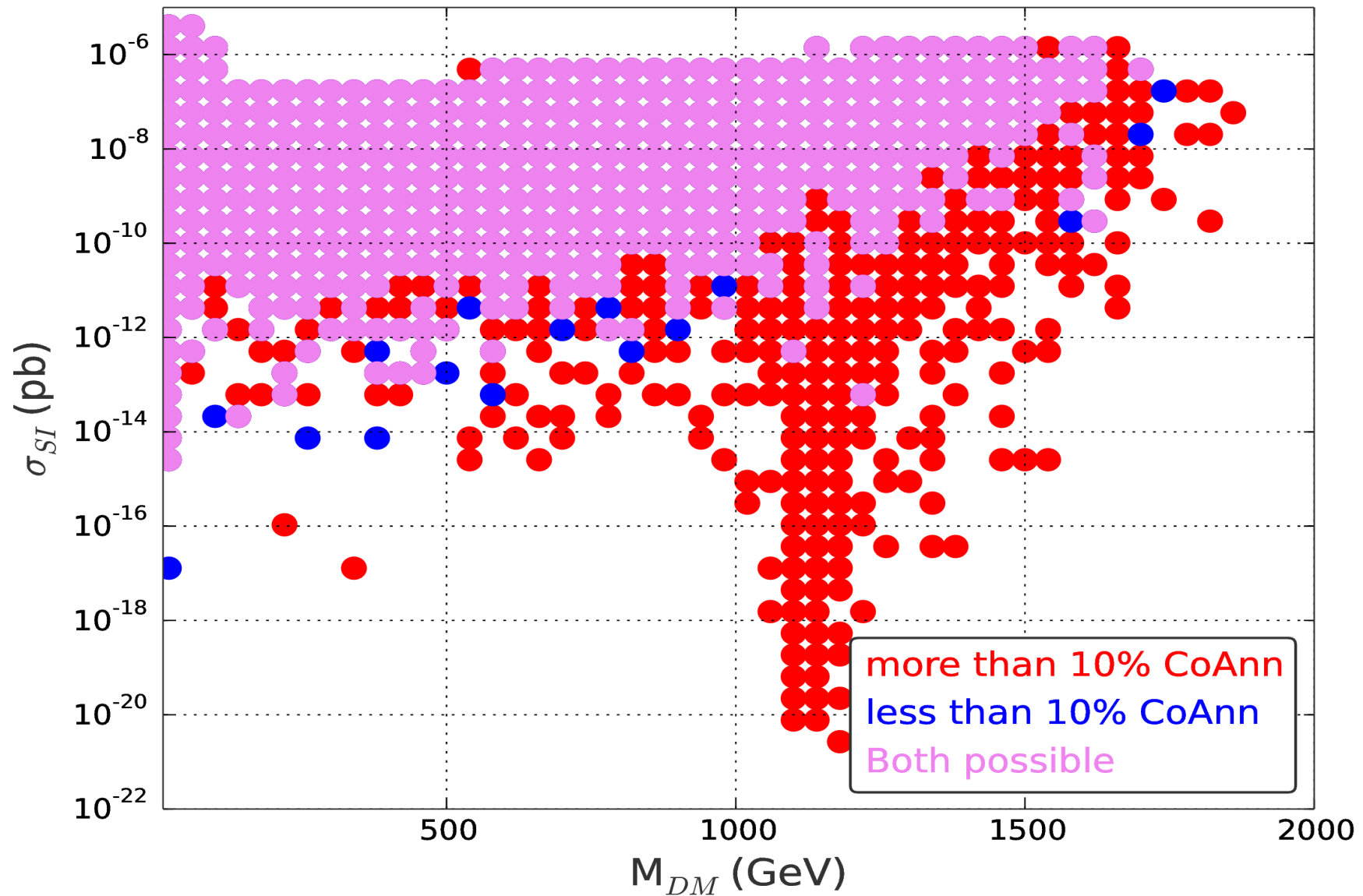
**Mixing** between **Majorana** singlet  $\psi_S$  and neutral left- and right handed **Dirac** doublet components  $\psi_{D,L}^0$  and  $\psi_{D,R}^0$

Three **Majorana** mass eigenstates  $\chi_i$

# Singlet doublet fermion dark matter

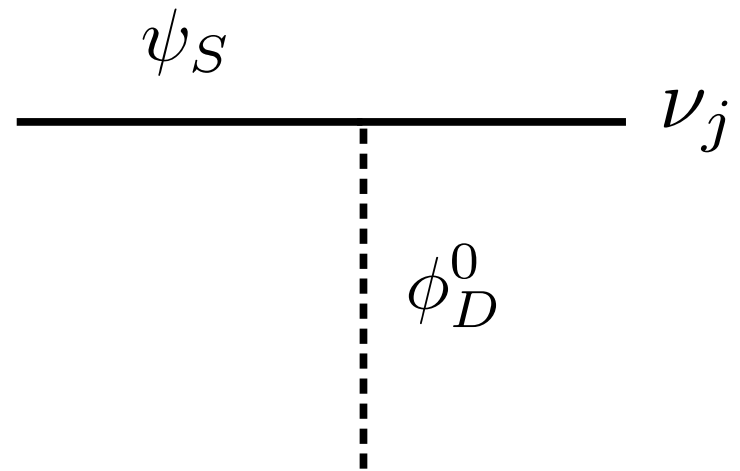
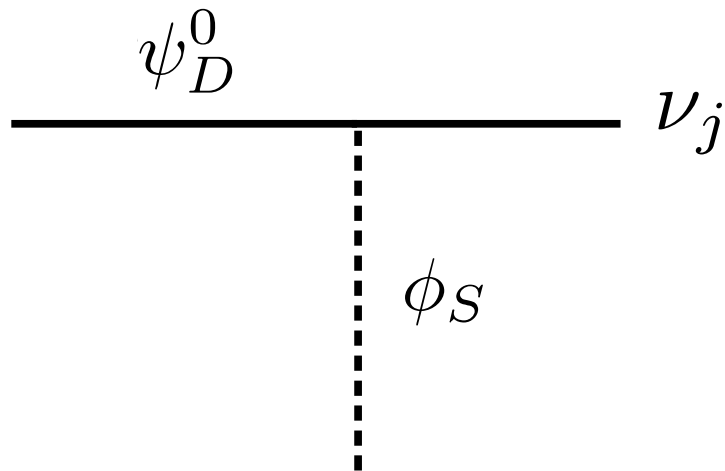


# Singlet doublet fermion dark matter



# Neutrino masses within T12A

Before EWSB:  $\mathcal{L}_{\text{lep}} = G_{1j} \Psi_D L_j \phi_S + G_{2j} \Psi_S L_j \phi_D$



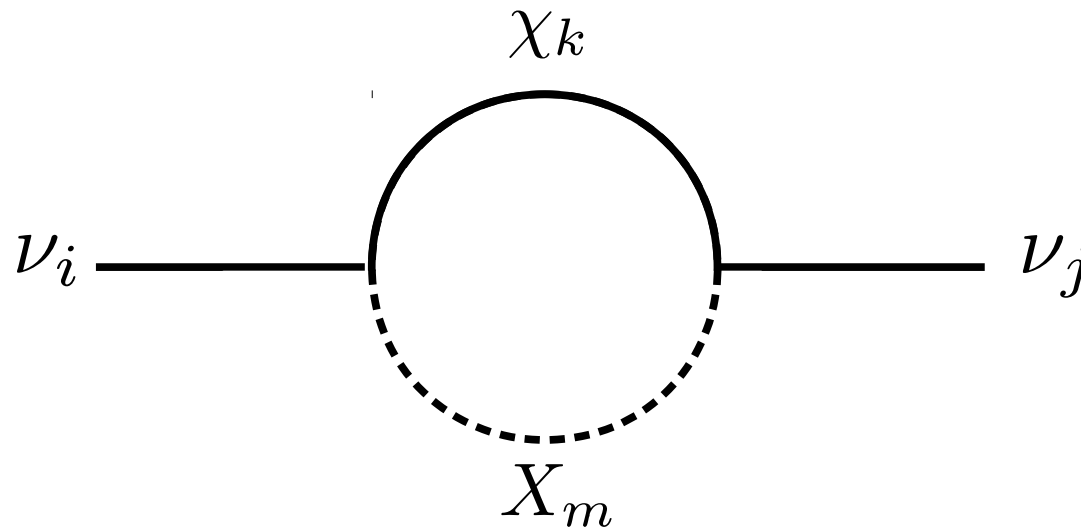
- Fermion doublet  $\Psi_D$
- Fermion singlet  $\Psi_S$
- Scalar doublet  $\phi_D$
- Scalar singlet  $\phi_S$
- Lepton doublet  $L_j$



# Neutrino masses within T12A

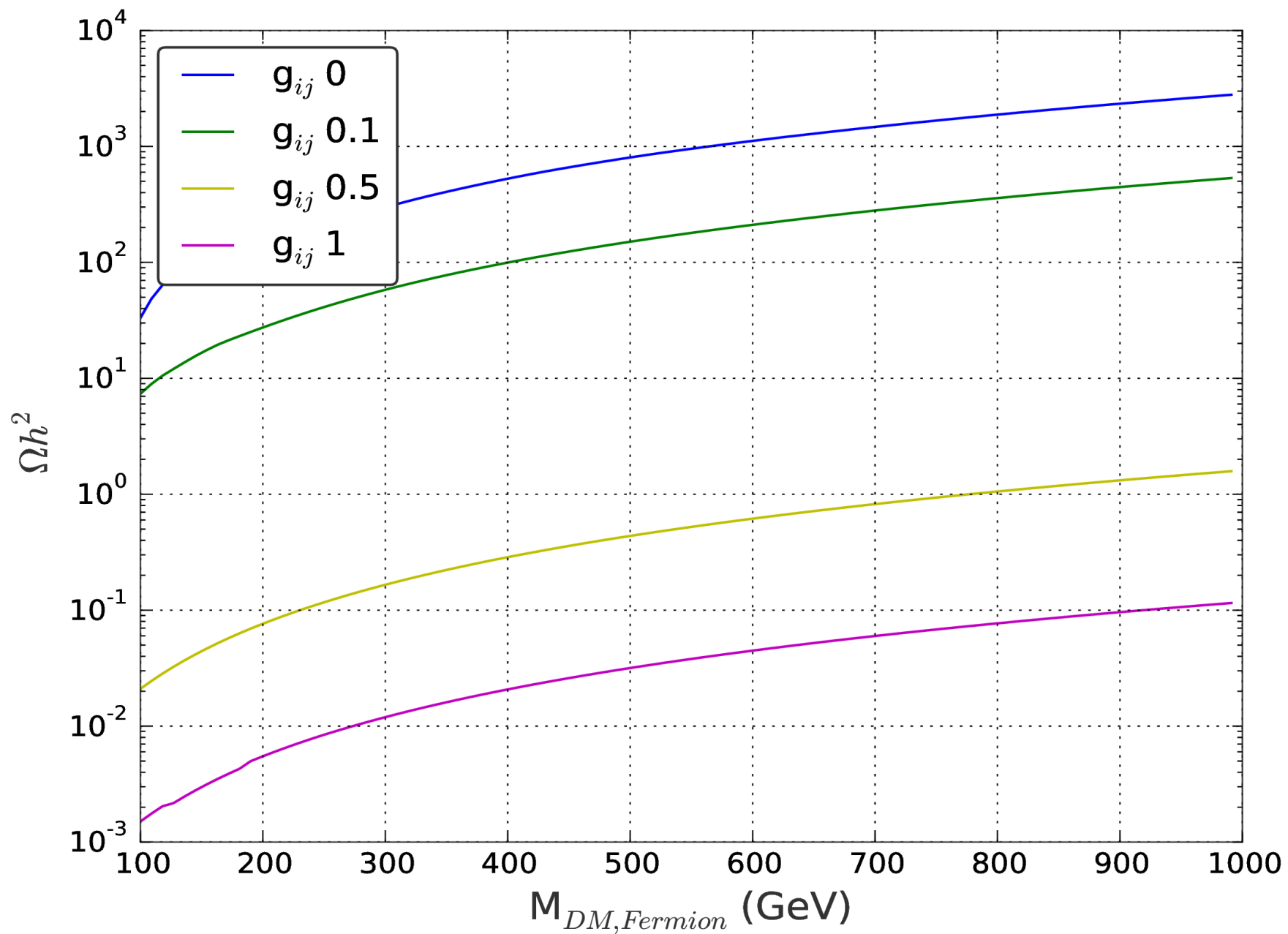
After EWSB:

$$\mathcal{L}_{\text{lep}} = G_{ijk} \chi_i \nu_j X_k$$

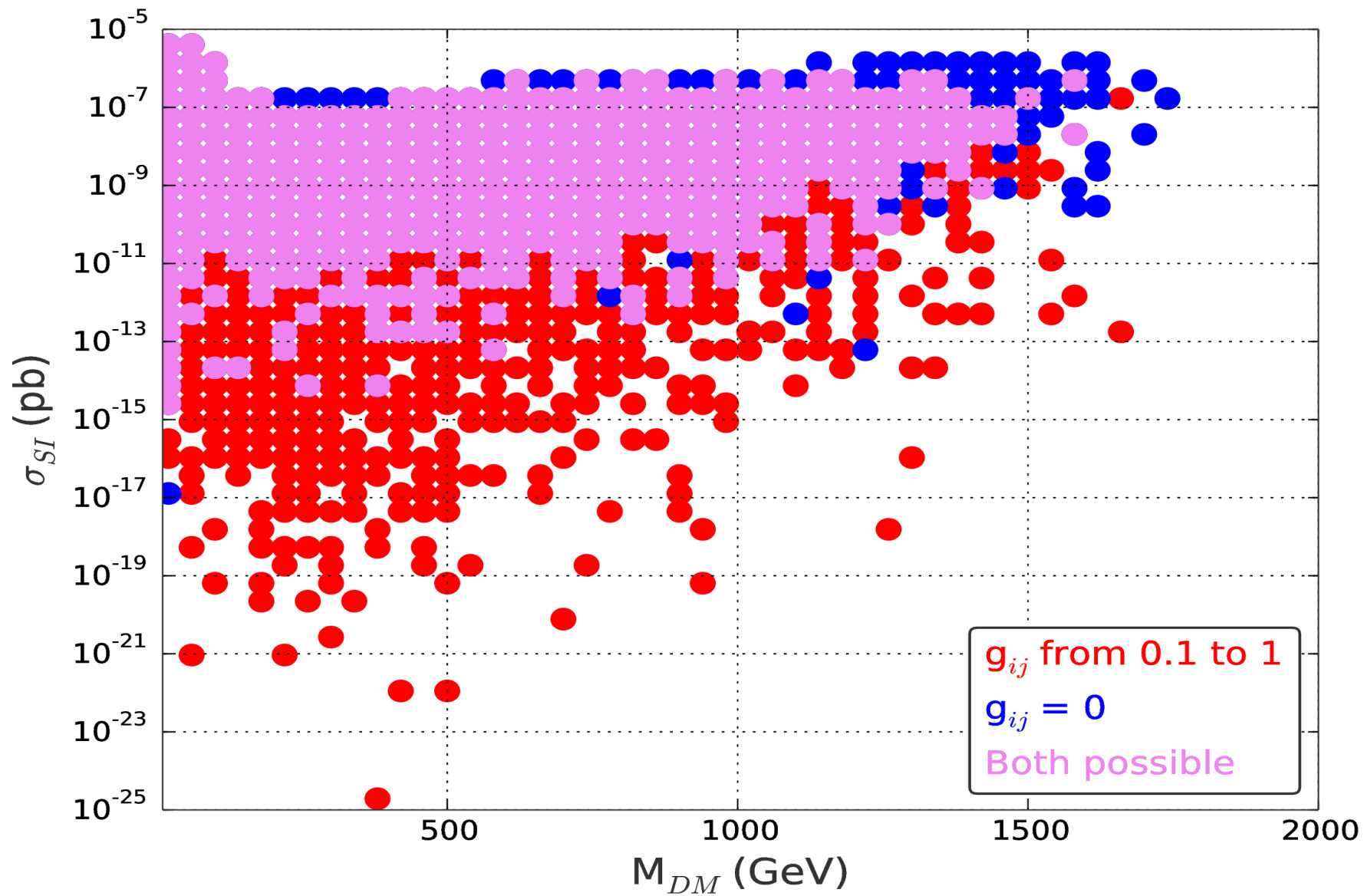


- Fermion  $\chi_k$
- Scalar  $X_m$
- Loop diagram: expression for neutrino mass matrix element  $\mathbf{m}_{ij}$
- Neutrino mixing

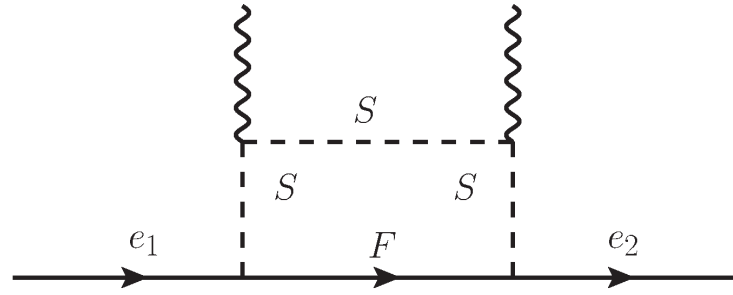
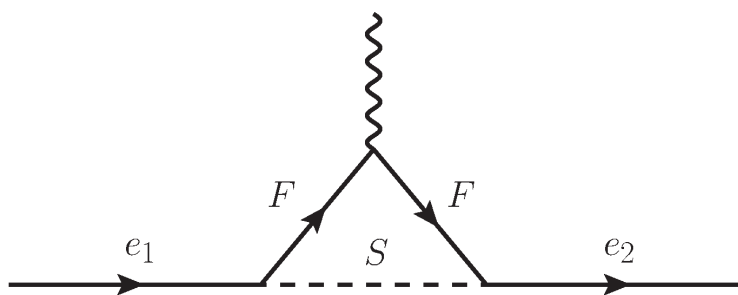
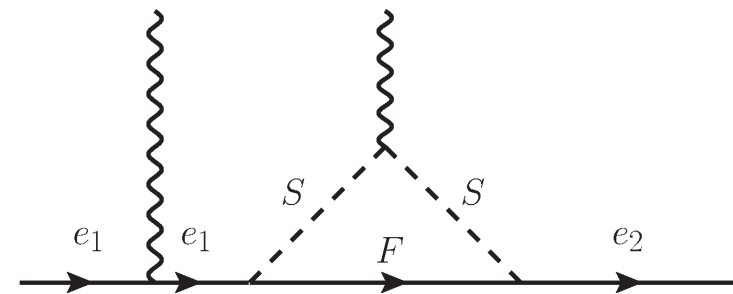
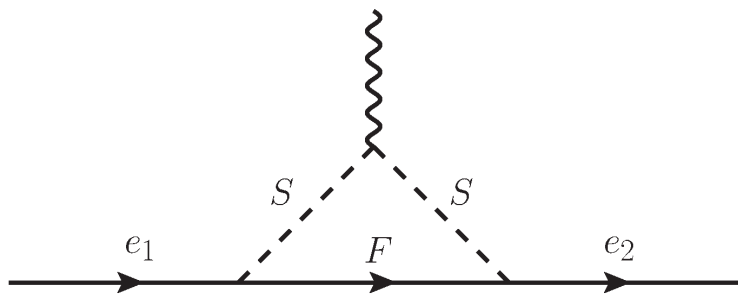
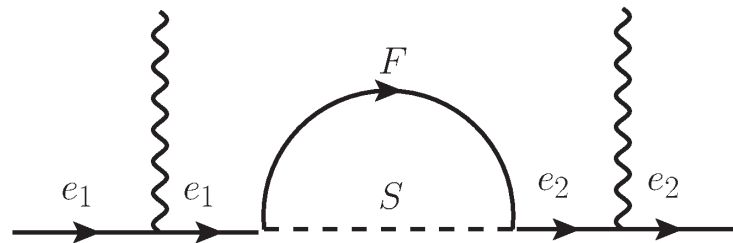
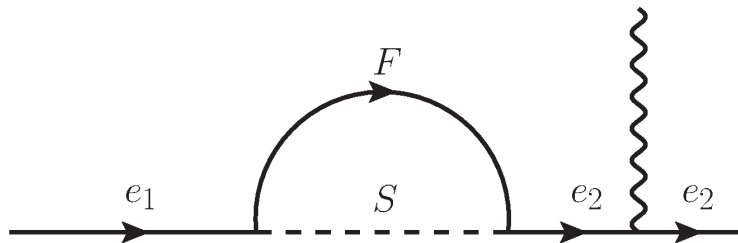
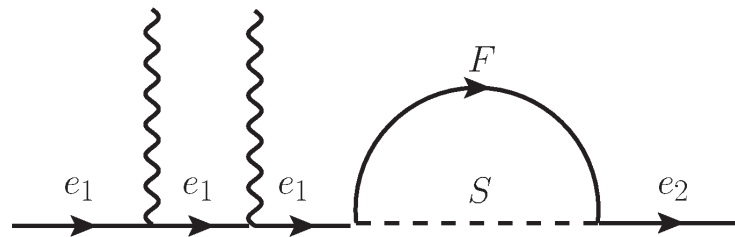
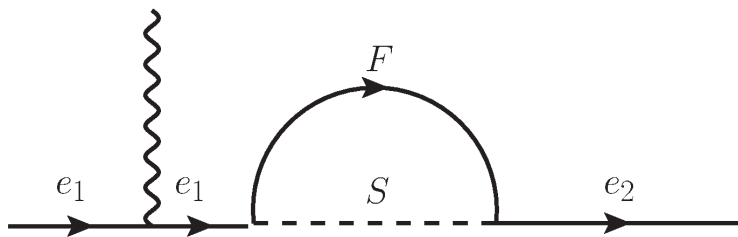
# Fermionic Dark Matter in T12A



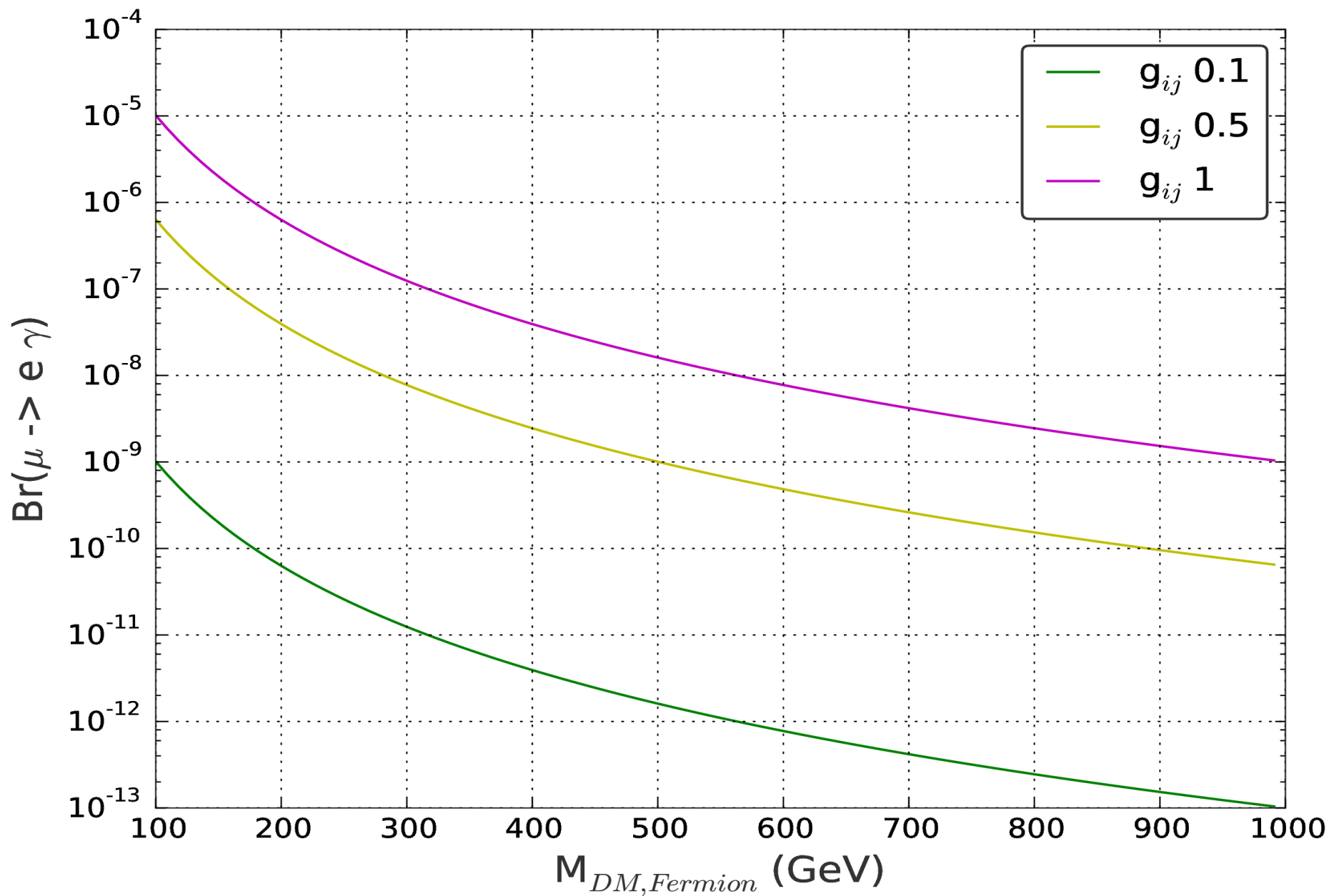
# Fermionic Dark Matter in T12A



# Lepton Flavour Violation



# Lepton Flavour Violation in T12A



# Summary and outlook

- Model T12A
  - New  $Z_2$  symmetry
  - Fermionic and scalar singlets and doublets
- Loop contributions generate neutrino mass
- Lightest odd particle: dark matter
  
- Dark matter observables:
  - Relic density
  - Direct detection cross section
  - Indirect detection signals
  
  - Neutrino physics
  - Higgs physics
  - Lepton flavor violating processes
  - ...

# References

- 1) D.~J. Fixsen. *The Astrophysical Journal*, 707:916--920, 2009
- 2) <http://www.astronomy.ohio-state.edu/~thompson/1144/Lecture40.html>
- 3) <http://chandra.harvard.edu/photo/2006/1e0657/more.html>
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- 5) [http://www.nobelprize.org/nobel\\_prizes/physics/laureates/2015/press.html](http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/press.html)
- 6) <https://neutel11.wordpress.com/2011/03/16/neutrino-mass-models-by-steveking/>
- 7) <https://inspirehep.net/record/1086544/plots>
- 8) [http://www.duden.de/\\_media\\_/full/G/Gewicht-201100277763.jpg](http://www.duden.de/_media_/full/G/Gewicht-201100277763.jpg)
- 9) <http://www.symmetrismagazine.org/article/february-2013/neutrinos-the-standard-model-misfits>
- 10) C.Cheung, D.Sanford - *JCAP* 02(2014)