MeV neutrino dark matter: relic density, lepton flavour violation and electron recoil

J. Fiaschi, M. Klasen, M. Vargas,
C. Weinheimer, S. Zeinstra

JHEP 11 (2019) 129

ICHEP 2020 | PRAGUE

40th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

VIRTUAL CONFERENCE

28 JULY - 6 AUGUST 2020

PRAGUE, CZECH REPUBLIC

Westfälische Wilhelms-Universität Münster

Topics of this talk

- **SLIM model with MeV neutrino DM:**
  - Motivations
  - Theory
  - Pheno

- **Current experimental tests:**
  - Collider
  - Cosmological
  - Neutrino
  - Lepton Flavour Violation

- **Electron recoil in Direct Detection Xenon1T**

- **Conclusions**

SLIM model

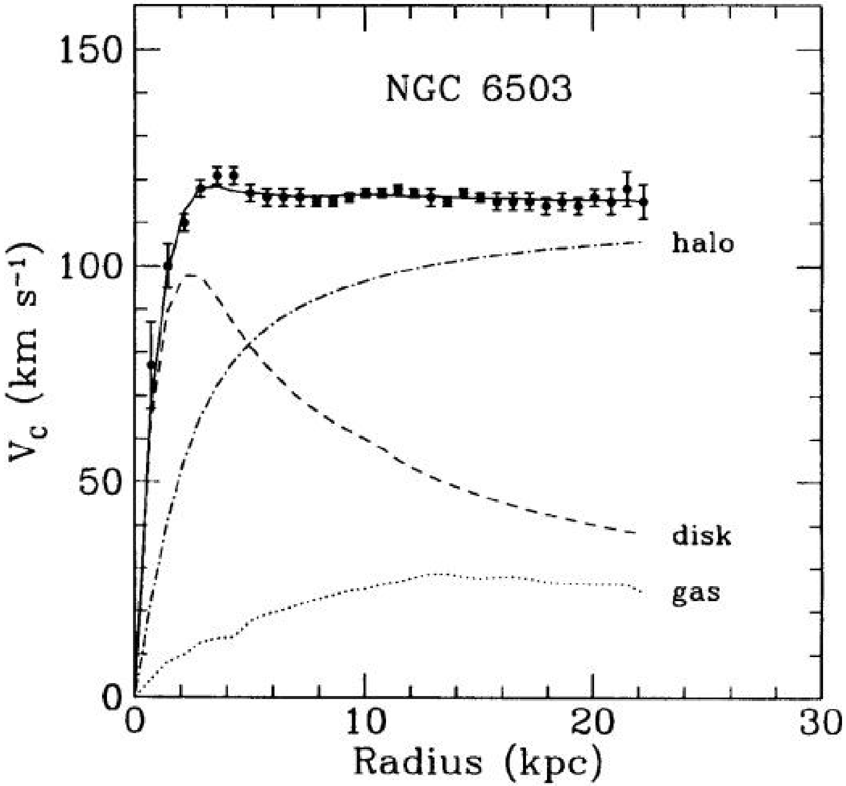
- **SLIM model with MeV neutrino DM:**
  - Motivations
  - Theory
  - Pheno

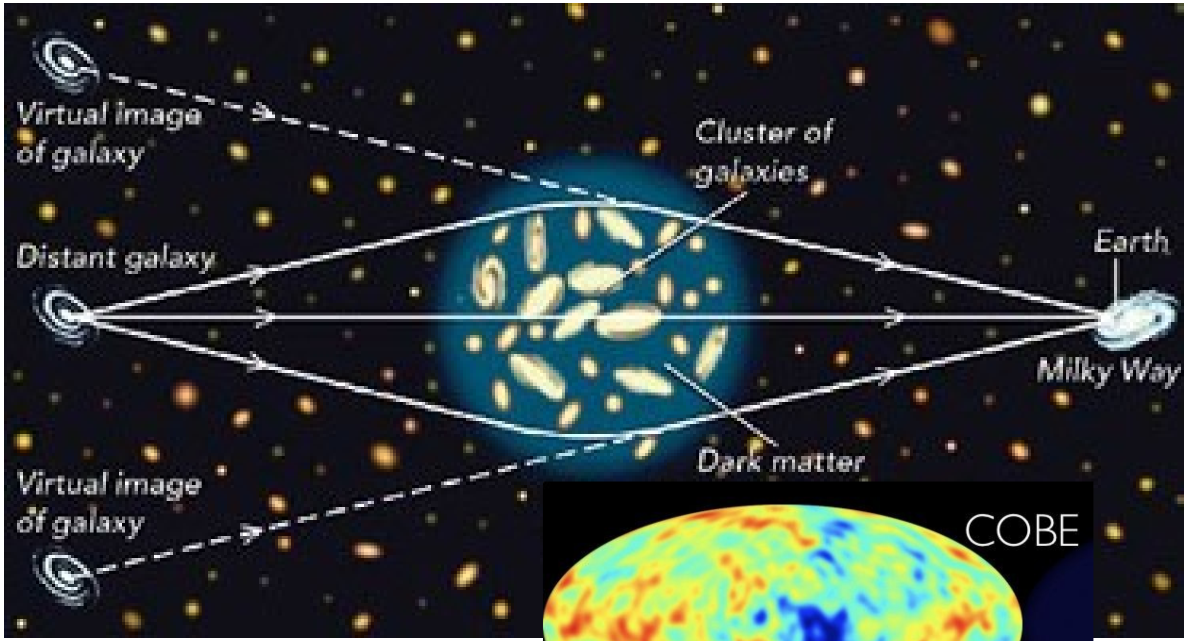
- **Current experimental tests:**
  - Collider
  - Cosmological
  - Neutrino
  - Lepton Flavour Violation

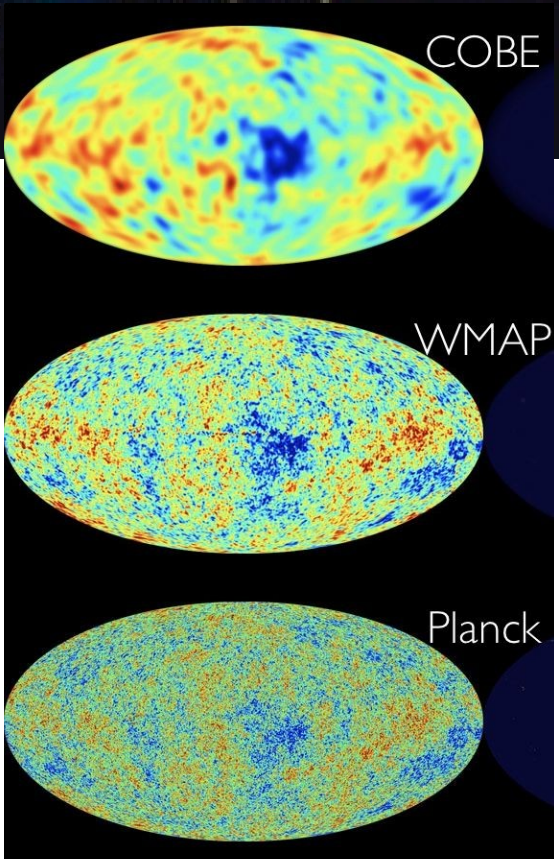
- **Electron recoil in Direct Detection Xenon1T**

- **Conclusions**

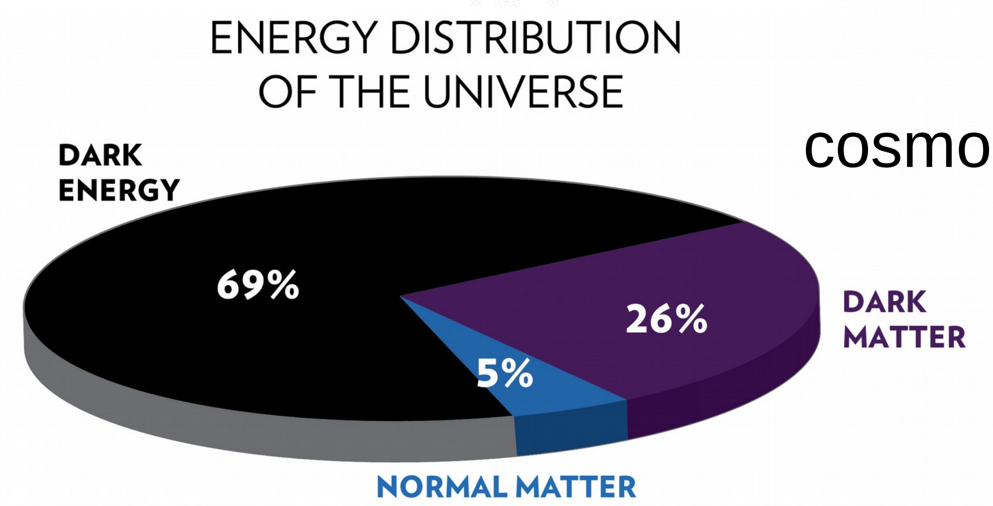
Evidences for Dark Matter



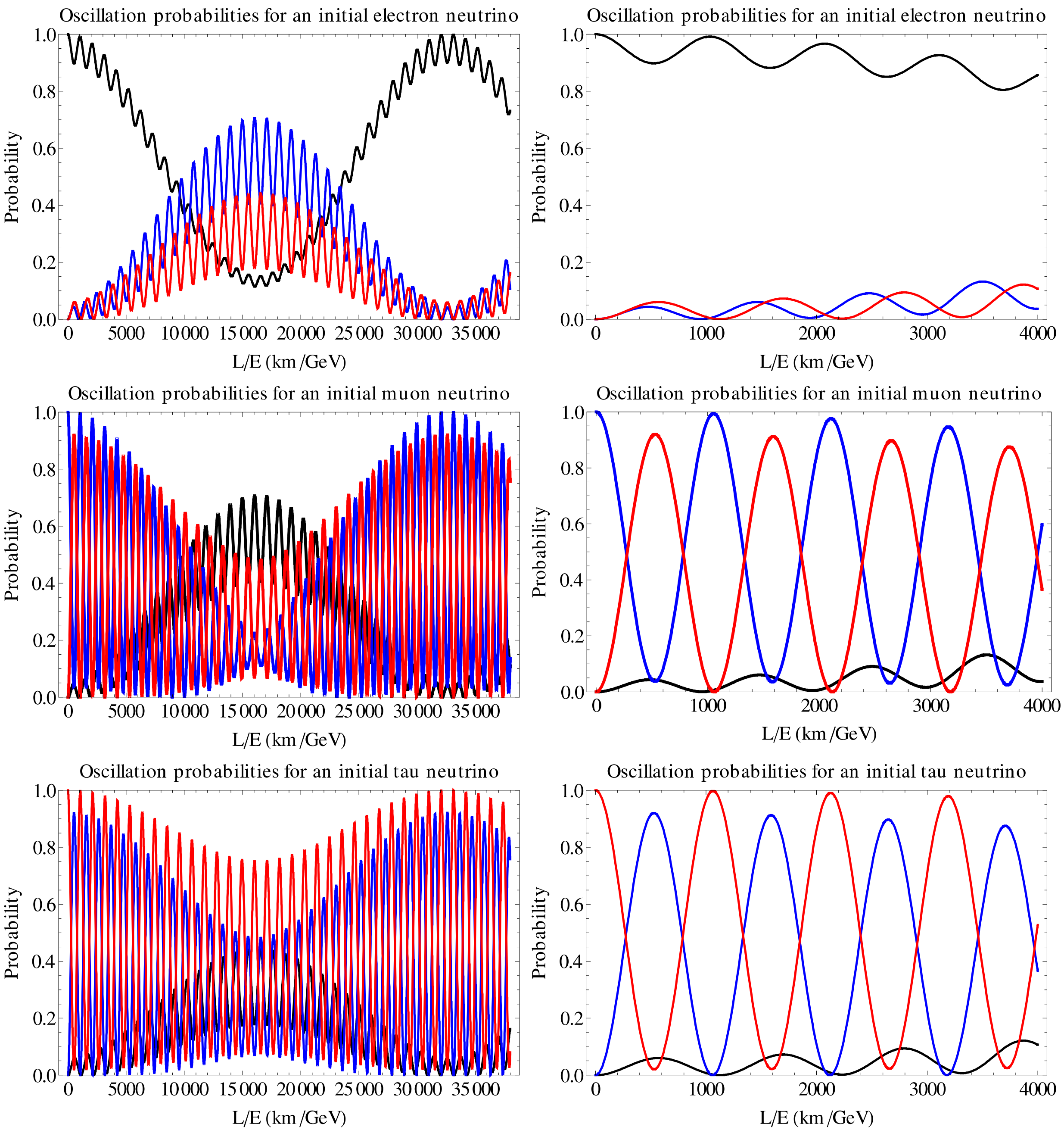


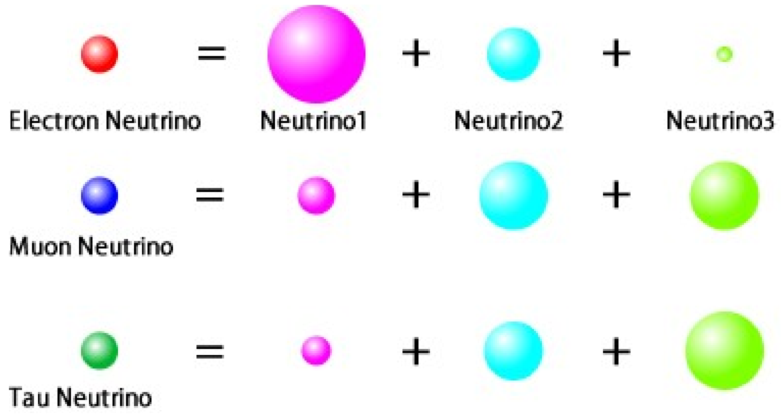


ΛCDM
cosmological model



Evidences for neutrino masses





The interpretation is:

Neutrinos have mass

Minimal models

Can we address both issues with a single BSM theory?
(A real pleasure for theorists)

Minimal DM models with radiative neutrino masses

Introduce the least possible amount of BSM fields

- $\leq$ 4 new scalar / fermion multiplets
- *SU(3)* color singlets
  SU(2) singlets, doublets, triplets
- Additional stabilising discrete Z_2 symmetry

Minimal models with these features have been classified according to the topology of the diagram generating the neutrino masses:

D. Restrepo, O. Zapata, C. E. Yaguna: **JHEP 1311 (2013) 011**

Examples:

"Scotogenic model" : E. Ma: **Phys.Rev. D73 (2006) 077301**
T1-3-A (α = 0) : S. Esch, M. Klasen, D. R. Lamprea, C. E. Yaguna: **Eur.Phys.J. C78 (2018) no.2, 88**
T1-2-A (α = 0) : S. Esch, M. Klasen, C. E. Yaguna: **JHEP 1810 (2018) 055**
T1-3-B (α = 0) : J. Fiaschi, M. Klasen, S. May: **JHEP 05 (2019) 015**

Why MeV Dark Matter?

Explanations for the large scale structore of the Universe favours the GeV to TeV cold DM regime.

However, **warm DM** seems to account better for:

- Missing satellite galaxies
  the number of dwarf satellite galaxies is much lower than the one expected from simulations.

- Too-big-to-fail problem
  the unobserved missing satellite galaxies would be still to big to have had their visible stars stripped from them.

- Cusp-core problem of inner DM density profile
  DM density appears flat at small radii (especially in low-mass galaxies) while simulations would predict a steeply increasing density at their core.

In this talk we present our study of the **SLIM** (Scalar as Light as MeV) model, in which the SM is augmented by:

- one complex scalar singlet: $\rho = \frac{1}{\sqrt{2}}(\rho_R + i\rho_I)$
- (at least) two generations of singlet right-handed neutrinos: N_i
- one complex scalar doublet: $\eta = \begin{pmatrix} \eta^+ \\ \frac{1}{\sqrt{2}}(\eta_R + i\eta_I) \end{pmatrix}$

The SLIM model - Theory

$$\mathcal{L} = -m_1^2\Phi^\dagger\Phi - m_2^2\eta^\dagger\eta - m_3^2\rho^*\rho - \underline{\frac{1}{2}m_4^2\left(\rho^2 + (\rho^*)^2\right)} - \mu(\eta^\dagger\Phi\rho + h.c.) - \underline{\frac{1}{2}m_{N_i}\overline{N_i^c}N_i}$$
$$-\frac{1}{2}\lambda_1(\Phi^\dagger\Phi)^2 - \frac{1}{2}\lambda_2(\eta^\dagger\eta)^2 - \frac{1}{2}\lambda_3(\rho^*\rho)^2 - \lambda_4(\eta^\dagger\eta)(\Phi^\dagger\Phi) - \lambda_5(\eta^\dagger\Phi)(\Phi^\dagger\eta)$$
$$-\lambda_6(\rho^*\rho)(\Phi^\dagger\Phi) - \lambda_7(\rho^*\rho)(\eta^\dagger\eta) - \underline{(\lambda_8)_{ij}\left(\overline{N_i^c}\eta^\dagger L_j + h.c.\right).}$$

Right-handed Majorana neutrinos

- They allow for neutrino mass generation through different variants of seesaw mechanism
- Help to restore parity at higher energy.
- If the seesaw mechanism is instead realised at one loop, we can connect DM and neutrino sectors.

Soft breaking of global U(1) symmetry to discrete Z_2. Implies small m_4.

- Forbids decay of lightest Z_2 odd particle, which becomes a viable DM candidate.

Model is leptophilic

- Novel study of the electron recoil signal in direct detection experiments (XENON1T)

The SLIM model - Pheno

$$\mathcal{L} = -m_1^2\Phi^\dagger\Phi - m_2^2\eta^\dagger\eta - m_3^2\rho^*\rho - \frac{1}{2}m_4^2\left(\rho^2 + (\rho^*)^2\right) - \mu(\eta^\dagger\Phi\rho + h.c.) - \frac{1}{2}m_{N_i}\overline{N_i^c}N_i$$
$$-\frac{1}{2}\lambda_1(\Phi^\dagger\Phi)^2 - \frac{1}{2}\lambda_2(\eta^\dagger\eta)^2 - \frac{1}{2}\lambda_3(\rho^*\rho)^2 - \lambda_4(\eta^\dagger\eta)(\Phi^\dagger\Phi) - \lambda_5(\eta^\dagger\Phi)(\Phi^\dagger\eta)$$
$$-\lambda_6(\rho^*\rho)(\Phi^\dagger\Phi) - \lambda_7(\rho^*\rho)(\eta^\dagger\eta) - (\lambda_8)_{ij}\left(\overline{N_i^c}\eta^\dagger L_j + h.c.\right).$$

After EWSB:

Charged scalar mass eigenstates: $m^2_{\eta^\pm} = m_2^2 + \frac{1}{2}\lambda_4 v^2$

Neutral components of complex singlet and doublet mix throught the trilinear coupling *μ*: $M^2_{R,I} = \begin{pmatrix} m_2^2 + (\lambda_4+\lambda_5)\frac{v^2}{2} & \mu\frac{v}{\sqrt{2}} \\ \mu\frac{v}{\sqrt{2}} & m_3^2 + \lambda_6\frac{v^2}{2} \pm m_4^2 \end{pmatrix} =: \begin{pmatrix} A & B \\ B & C_{R,I} \end{pmatrix}$

The small m_4 parameter leads to almost degenracy of real and imaginary scalar masses eigenstates: $m^2_{R,I} = \frac{1}{2}\left(A + C_{R,I} \pm \sqrt{(A - C_{R,I})^2 + 4B^2}\right)$

We parametrize the small splitting with the parameter *ε*: $AC_{R,I} - B^2 =: \epsilon(A + C_{R,I})$

A small value of *ε* will allow for two MeV neutral scalar mass eigenvalues, while the other two will remain as heavy as their charged counterpart.

Experimental tests

- **SLIM model with MeV neutrino DM:**
  - Motivations
  - Theory
  - Pheno

- **Current experimental tests:**
  - Collider
  - Cosmological
  - Neutrino
  - Lepton Flavour Violation

- **Electron recoil in Direct Detection Xenon1T**

- **Conclusions**

Collider constrains

$$\mathcal{L} = -m_1^2\Phi^\dagger\Phi - m_2^2\eta^\dagger\eta - m_3^2\rho^*\rho - \frac{1}{2}m_4^2\left(\rho^2 + (\rho^*)^2\right) - \mu(\eta^\dagger\Phi\rho + h.c.) - \frac{1}{2}m_{N_i}\overline{N_i^c}N_i$$
$$-\frac{1}{2}\lambda_1(\Phi^\dagger\Phi)^2 - \frac{1}{2}\lambda_2(\eta^\dagger\eta)^2 - \frac{1}{2}\lambda_3(\rho^*\rho)^2 - \lambda_4(\eta^\dagger\eta)(\Phi^\dagger\Phi) - \lambda_5(\eta^\dagger\Phi)(\Phi^\dagger\eta)$$
$$-\lambda_6(\rho^*\rho)(\Phi^\dagger\Phi) - \lambda_7(\rho^*\rho)(\eta^\dagger\eta) - (\lambda_8)_{ij}\left(\overline{N_i^c}\eta^\dagger L_j + h.c.\right).$$

m_1 and λ_1 are fixed by Higgs potential.

For negligible m_4 the coupling between scalars reads:

$$\begin{pmatrix}\eta\\ \rho\end{pmatrix}^\dagger \begin{pmatrix}(\lambda_4+\lambda_5)v & \frac{\mu}{\sqrt{2}}\\ \frac{\mu}{\sqrt{2}} & \lambda_6 v\end{pmatrix}\Phi\begin{pmatrix}\eta\\ \rho\end{pmatrix}$$

Thus we identify: $m_2^2 = (\lambda_4+\lambda_5)\dfrac{v^2}{2}$ and $m_3^2 = \lambda_6\dfrac{v^2}{2}$

The masses of charged scalar particles are constrained by model independent limits from LEP.

OPAL collaboration: **Phys.Lett. B 572 (2003) 8**

The coupling between the Higgs and the charged scalars is constrained by the experimental measurements on the BR of Higgs into two photons.

$$R_{\gamma\gamma} = 1.20^{+0.18}_{-0.14}$$

CMS collaboration: **Eur.Phys.J. C 79 (2019) 421**

Both constrains are satisfied setting: $\lambda_{4,5} \approx 0.1$

(larger values are allowed but would lead to smaller electron recoil cross sections and lepton flavour violation)

Cosmological constrains

$$\mathcal{L} = -m_1^2\Phi^\dagger\Phi - m_2^2\eta^\dagger\eta - m_3^2\rho^*\rho - \frac{1}{2}m_4^2\left(\rho^2 + (\rho^*)^2\right) - \mu(\eta^\dagger\Phi\rho + h.c.) - \frac{1}{2}m_{N_i}\overline{N_i^c}N_i$$
$$-\frac{1}{2}\lambda_1(\Phi^\dagger\Phi)^2 - \frac{1}{2}\lambda_2(\eta^\dagger\eta)^2 - \frac{1}{2}\lambda_3(\rho^*\rho)^2 - \lambda_4(\eta^\dagger\eta)(\Phi^\dagger\Phi) - \lambda_5(\eta^\dagger\Phi)(\Phi^\dagger\eta)$$
$$-\lambda_6(\rho^*\rho)(\Phi^\dagger\Phi) - \lambda_7(\rho^*\rho)(\eta^\dagger\eta) - (\lambda_8)_{ij}\left(\overline{N_i^c}\eta^\dagger L_j + h.c.\right).$$

Missing satellite galaxies, cusp-core and too-big-to-fail problems can be solved by MeV neutrino DM, provided that it scatters off the active neutrinos in the early Universe by exchanging only slightly heavier scalars.

→ Singled and doublet masses have to be close to each other

$\lambda_{2,3,7}$ only concern processes of conversion of scalar particles (small phenomenological impact):

→ $\lambda_2 = 0.12$, $\lambda_3 = 0.13$, $\lambda_7 = 0.17$

m_3 should be not much larger than v, (i.e. $\lambda_6 \leq 3$):

→ Fix $\lambda_2 = 2.3$, vary ε

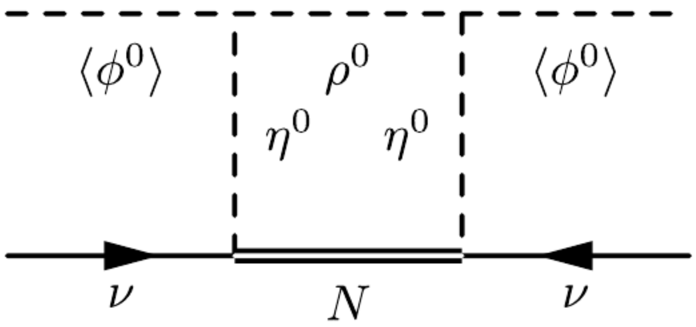
In order not to erase primordial DM fluctuation, for MeV DM and weak DM self-interactions, we need a small mass difference between MeV neutrino DM and the lightest scalar:

→ Ratio of N_1 mass over lightest scalar mass in the range [0.1, 0.98]

Neutrino constrains

Z_2 symmetry forbids tree level see-saw mechanism.
Neutrino masses are generated radiatively:

(In the aforementioned classification of minimal models, the SLIM model corresponds to model T1-1-A with hypercharge parameters α = 0)



Neutrino masses are given by: $$(M_\nu)_{ij} = \sum_k \frac{(\lambda_8)_{ik}(\lambda_8)_{jk}}{16\pi^2} m_{N_k} \left[\frac{\cos^2\theta_R m_{1R}^2}{m_{1R}^2 - m_{N_k}^2} \ln\frac{m_{1R}^2}{m_{N_k}^2} + \frac{\sin^2\theta_R m_{2R}^2}{m_{2R}^2 - m_{N_k}^2} \ln\frac{m_{2R}^2}{m_{N_k}^2} - \frac{\cos^2\theta_I m_{1I}^2}{m_{1I}^2 - m_{N_k}^2} \ln\frac{m_{1I}^2}{m_{N_k}^2} - \frac{\sin^2\theta_I m_{2I}^2}{m_{2I}^2 - m_{N_k}^2} \ln\frac{m_{2I}^2}{m_{N_k}^2} \right]$$

We take the experimental constrains from neutrino measurements into account by fixing the coupling λ_8 by means of the Casas-Ibarra parametrization:

J.A. Casa, A. Ibarra: **Nucl.Phys. B 618 (2001) 171**

$$\boxed{\lambda_8 = M^{-1/2} R D_\nu^{1/2} U_\nu^\dagger}$$

With $M_\nu = \lambda_8^T M \lambda_8$ $\quad R = \begin{pmatrix} 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix}$ $\quad D_\nu = U_\nu^\dagger M_\nu U_\nu = \mathrm{diag}(0, m_{\nu 2}, m_{\nu 3})$

And U_ν being the PMNS neutrino mixing matrix

Parameter scan range

Parameter	Value	Range	Phenomenological impact
m_1^2	$-(89\,\mathrm{GeV})^2$	–	Fixed by v and m_h
m_2	$83\,\mathrm{GeV}$	–	Fixed by v, λ_4 and λ_5
m_3	$264\,\mathrm{GeV}$	–	Fixed by v and λ_6
m_4	–	$10\,\mathrm{keV} \ldots 10\,\mathrm{MeV}$	Induces soft U(1) breaking
μ	–	$251\,\mathrm{GeV} \ldots 252\,\mathrm{GeV}$	Fixed by v and ϵ
ϵ	–	$(10^{-5} \ldots 6.1 \cdot 10^{1})\ \mathrm{GeV}^2$	Induces MeV masses
m_{N_1}	–	$(0.1 \ldots 0.98) \cdot m_{\zeta_2}$	$\mathcal{O}(\mathrm{MeV})$ DM candidate
m_{N_2}	–	$10\,\mathrm{GeV} \ldots 200\,\mathrm{GeV}$	$\mathcal{O}(\mathrm{GeV})$ sterile neutrino
λ_1	0.26	–	Fixed by v and m_h
λ_2	0.12	–	Induces only scalar conversions
λ_3	0.13	–	Induces only scalar conversions
λ_4	0.097	–	Fixed by v, $m_{\eta^\pm} = 99\,\mathrm{GeV}$, $R_{\gamma\gamma}$
λ_5	0.13	–	Fixed by v, $m_{\eta^\pm} = 99\,\mathrm{GeV}$, $R_{\gamma\gamma}$
λ_6	2.3	–	Induces MeV masses
λ_7	0.17	–	Induces only scalar conversions
λ_8	–	$10^{-6} \ldots 10^{2}$	Fixed by Casas-Ibarra parametr.

CHAIN OF TOOLS:

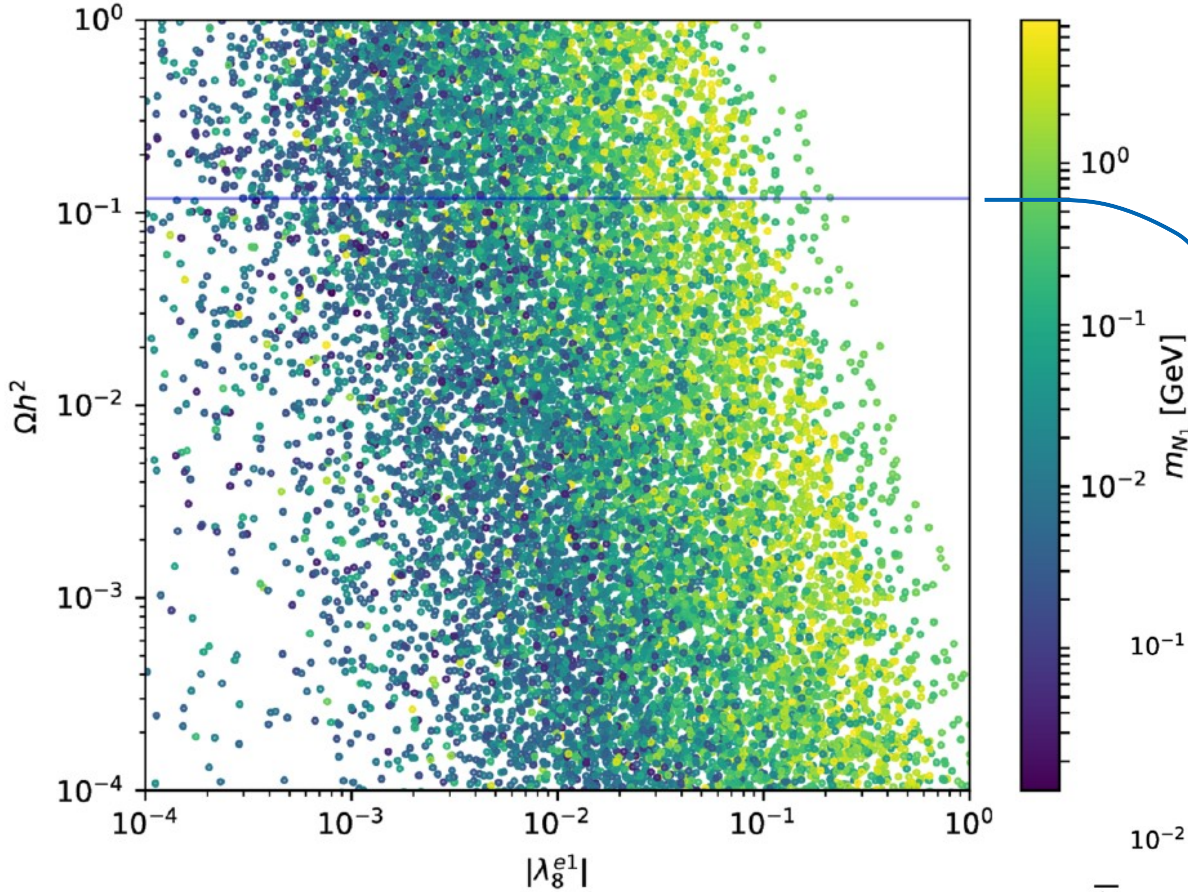
1) **MINIMAL-LAGRANGIANS** (in-house tool for generating input Lagrangian for SLIM model)

2) **SARAH 4.14.2** (for generating Feynman rules and compilable SPheno and MICROmegas models and main files)

3) **SPheno 4.0.3** (for generating the spectrum of each parameter space point, for collider and low energy observables as lepton flavour violation)

4) **MICROmegas 4.3.5** (for calculating the relic density at each parameter space point)

Relic density constrains

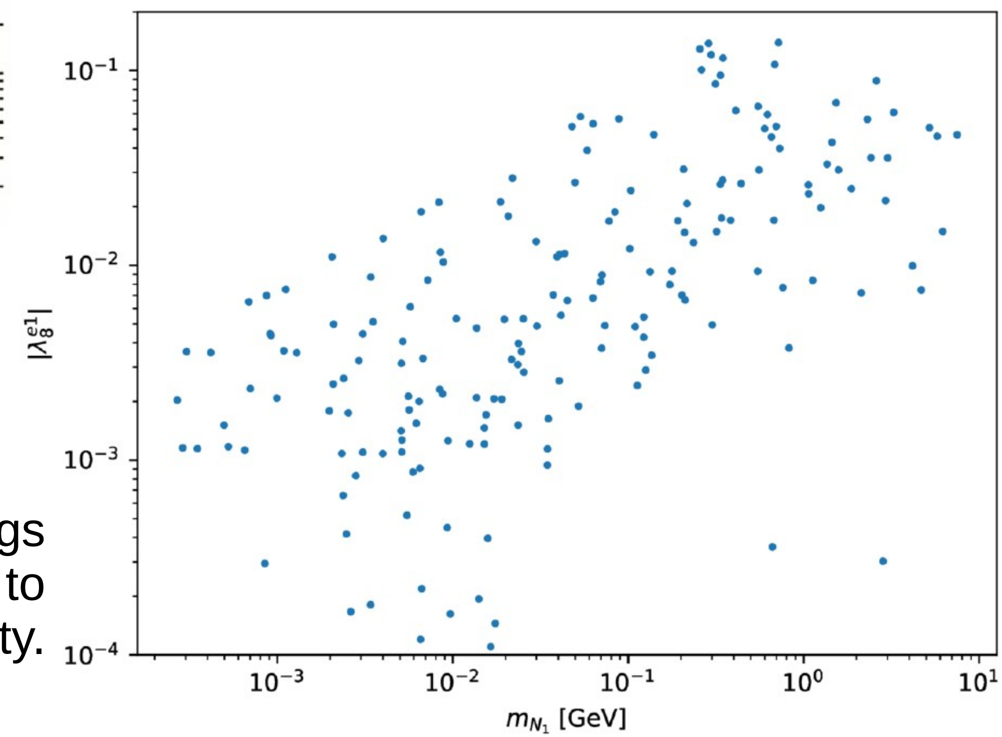


Planck measurements
on the DM relic density:

$$\Omega h^2 = 0.1186 \pm 0.0020$$

PLANCK collaboration: **arxiv:1807.06209**

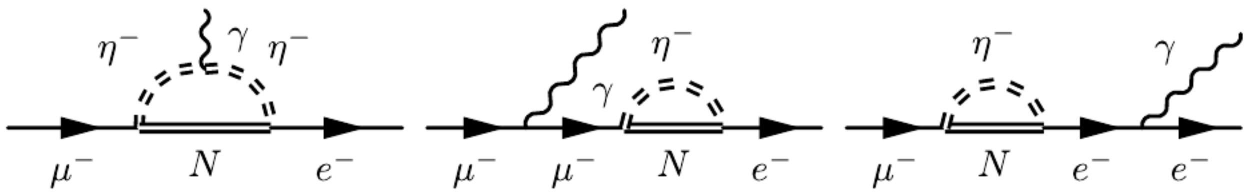
projection over the correct relic density

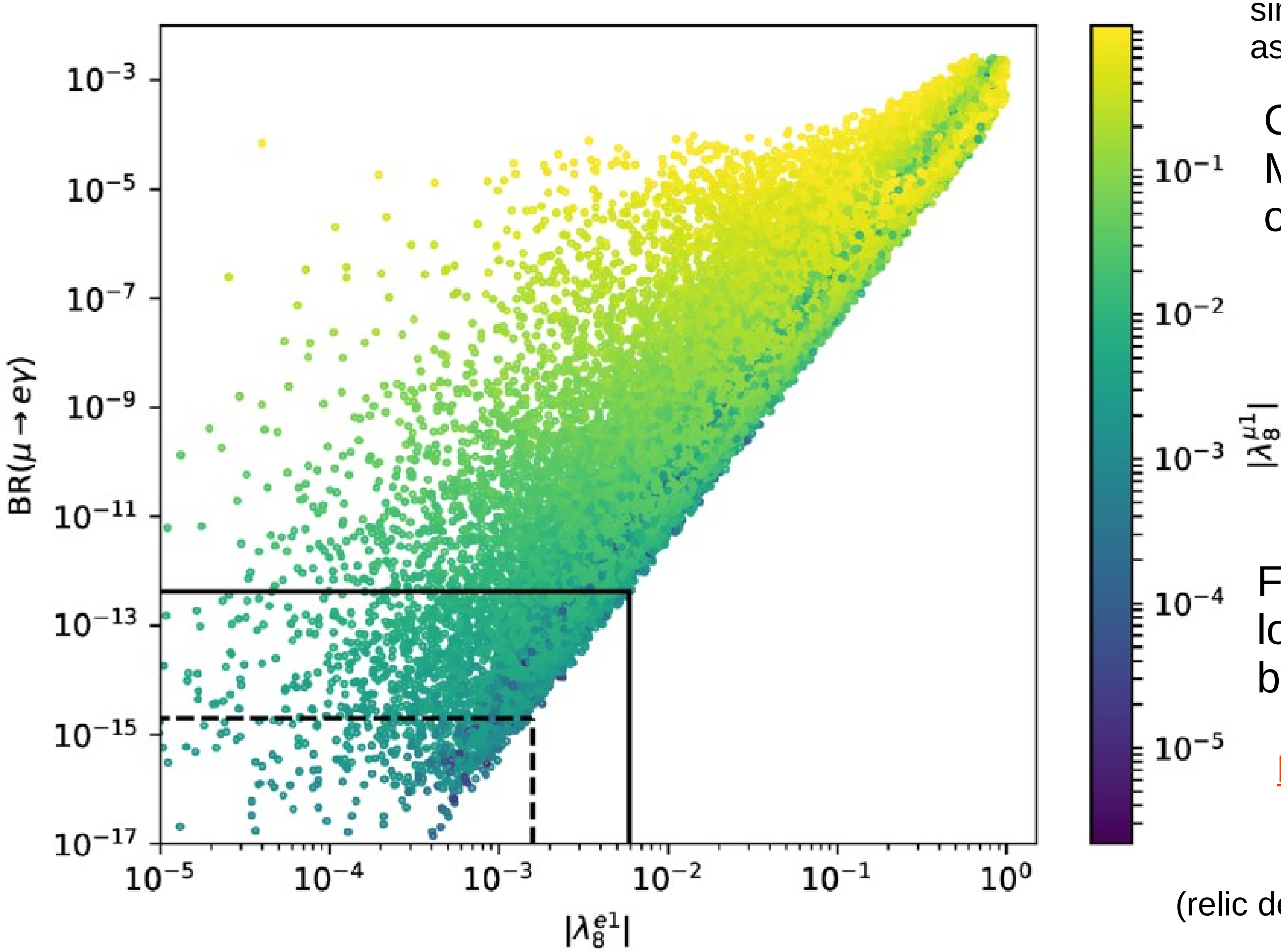


Relic density dropping quickly when increasing the lepton coupling.

Heavier DM mass implies larger couplings to leptons (enhanced DM annihilation) to obtain the correct relic density.

Lepton flavour violation constrains





Diagrams contributing to LFV

$\mu \to e\gamma$

(most sensitive process, thou other experiments will reach similar sensitivity in the future such as $\mu \to 3e$ and $\mu^- \mathrm{Ti} \to e^- \mathrm{Ti}$)

Current measurements from MEG experiment set constrains on leptonic couplings:

MEG collaboration:
Eur.Phys.J. C 76 (2016) 434

$\lambda_8^{ei} < 6 \times 10^{-3}$

$\lambda_8^{\mu i} < 10^{-2}$

Future measurements would lower the limits on the couplings by about a factor of 4.

F. Renga:
Hyperfine Interact. 239 (2018) 58

(relic density constrains are not imposed here)

Electron recoil

- **SLIM model with MeV neutrino DM:**
  - Motivations
  - Theory
  - Pheno

- **Current experimental tests:**
  - Collider
  - Cosmological
  - Neutrino
  - Lepton Flavour Violation

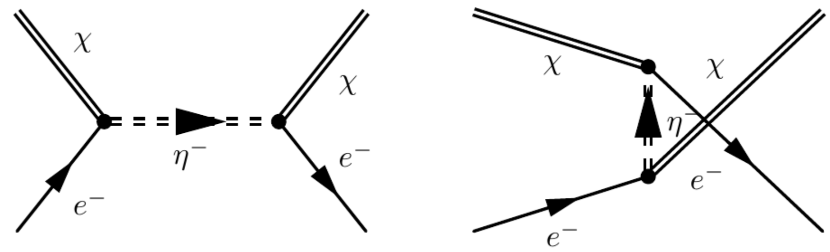
- **Electron recoil in Direct Detection Xenon1T**

- **Conclusions**

Electron recoil sensitivity study

LFV sets strong constrains on the couplings to leptons.

Nevertheless we expect some signal from electron recoil.



Ionization rate:

$$\frac{dR_{\rm ion}}{d\ln E_{\rm er}} = N_{\rm T}\frac{\rho_\chi}{m_\chi}\sum_{n\ell}\frac{d\langle\sigma_{\rm ion}^{n\ell}v\rangle}{d\ln E_{\rm er}}$$

N_T : # target nuclei per unit mass

ρ_χ = 0.4 GeV/cm^3 : local DM density

J.I. Read: **J. Phys. G 41 (2014) 063101**

Thermally averaged differential cross section:

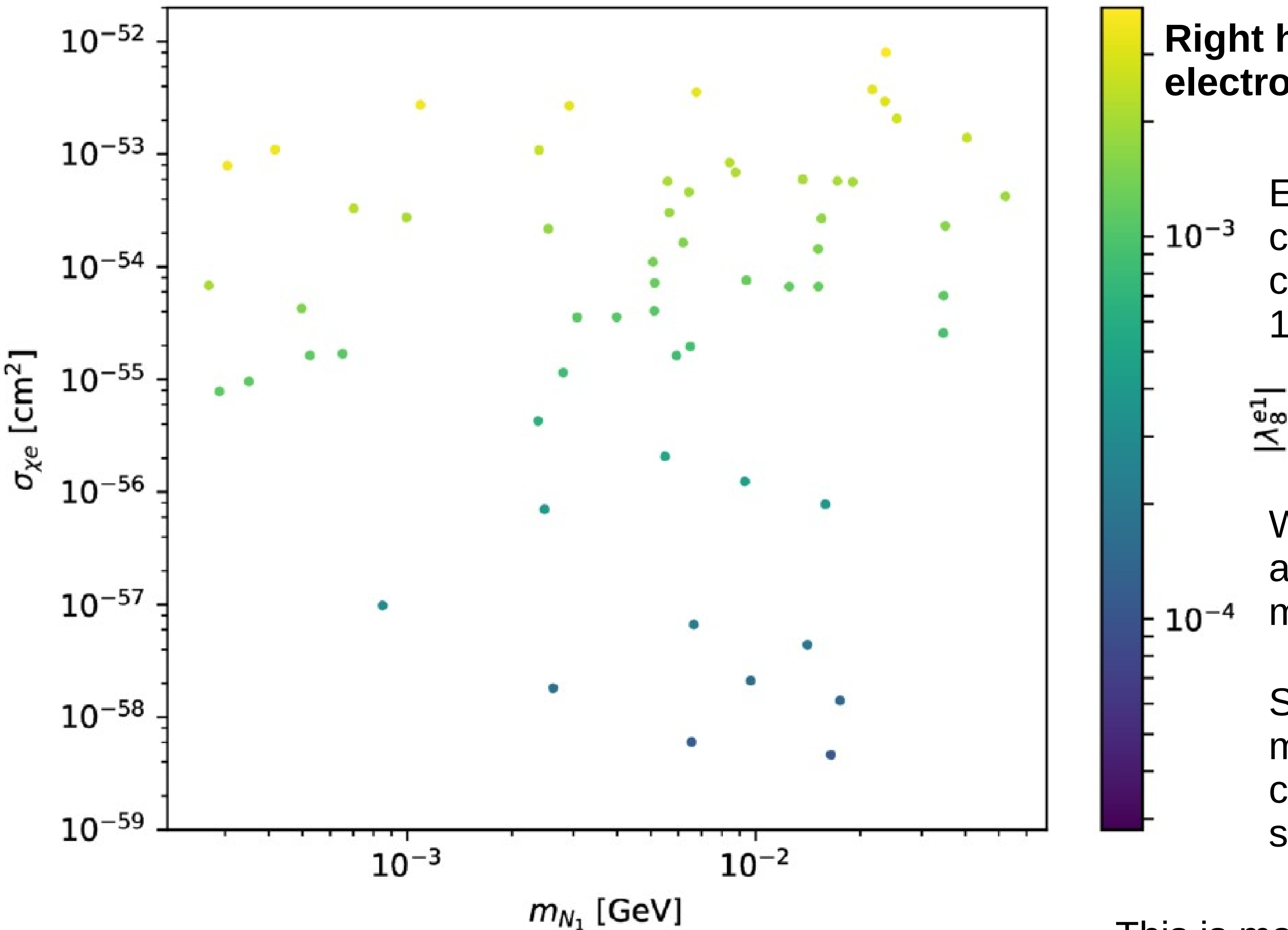
$$\frac{d\langle\sigma_{\rm ion}^{n\ell}v\rangle}{d\ln E_{\rm er}} = \boxed{\frac{\bar\sigma_{\chi e}}{8\mu_{\chi e}^2}}\int \boxed{|f_{\rm ion}^{n\ell}(k',q)|^2 F(k',Z_{\rm eff})}|F_{\rm DM}(q)|^2\boxed{\eta(v_{\rm min},t)}\; q\; dq$$

Nuclear and atomic physics enters in:
- Ionization form factor
- Correction of wave function of escaping electron (Fermi function)

Astrophysics enters in:
- Mean inverse DM velocity (Standard Halo Model)

Particle physics enters in:
- DM-electron cross section (Form factor F_{DM} = 1 for heavy mediators)

Electron recoil sensitivity study



Right handed neutrino DM-electron cross section

Even for the largest couplings, the total cross section is at most 10^{-46} cm^2

When LFV constrains are imposed, we get at most 10^{-52} cm^2

Several orders of magnitude below current sensitivity at such low DM masses.

This is mainly driven by the large mass of the mediator $\eta^{\pm}$

Conclusions

- **SLIM model with MeV neutrino DM:**
  - Motivations
  - Theory
  - Pheno

- **Current experimental tests:**
  - Collider
  - Cosmological
  - Neutrino
  - Lepton Flavour Violation

- **Electron recoil in Direct Detection Xenon1T**

- **Conclusions**

Conclusions

- We explored the constrains on the **SLIM** model, where the SM is augmented with right-handed neutrinos, a scalar (complex) singlet and a scalar (complex) doublet.

- The lightest right handed neutrinos with MeV to GeV masses can explain the observed DM aboundance, and it can account for missing satellite, cusp-core and the too-big-to fail cosmological problems.

- The new scalars and their interactions with the right handed neutrinos provide a mechanism to generate the observed small neutrino masses at one-loop.

- We performed a scan over the parameter space of the model, selecting specific realizations that satisfy collider constrains, reproduce the observed SM neutrino mass differences and lead to the correct observed relic density.

- The viable points are predicted with relatively large couplings also with the SM charged leptons, thus we analysed the impact of current and future constrains from LFV experiments.
  Those turned out to strongly constrain further the parameter space of the model.

- We investigated the pontential sensitivity on this model from electron recoil signals in direct detection experiments (XENON and others).
  Due to the heavy mediator mass and the constrains on the couplings to leptons from LFV experiments, the resulting DM-electron cross section turned out to be significantly smaller than current experimental sensitivity.

Thank you!

Casas-Ibarra parametrization

Factorize explicit dependence on the couplings from neutrino mass matrix:

$$M_\nu = \lambda_8^T M \lambda_8$$

Neutrino mass matrix can be diagonalized using PMNS matrix:

$$D_\nu = U_\nu^\dagger M_\nu U_\nu = \mathrm{diag}(0, m_{\nu 2}, m_{\nu 3})$$

Combining this two expression we can write:

$$D_\nu = U_\nu^\dagger \lambda_8^T M \lambda_8 U_\nu$$

equivalently:

$$\mathrm{diag}(0,1,1) = D_\nu^{-1/2} U_\nu^\dagger \lambda_8^T M \lambda_8 U_\nu D_\nu^{-1/2} \equiv R^\dagger R$$

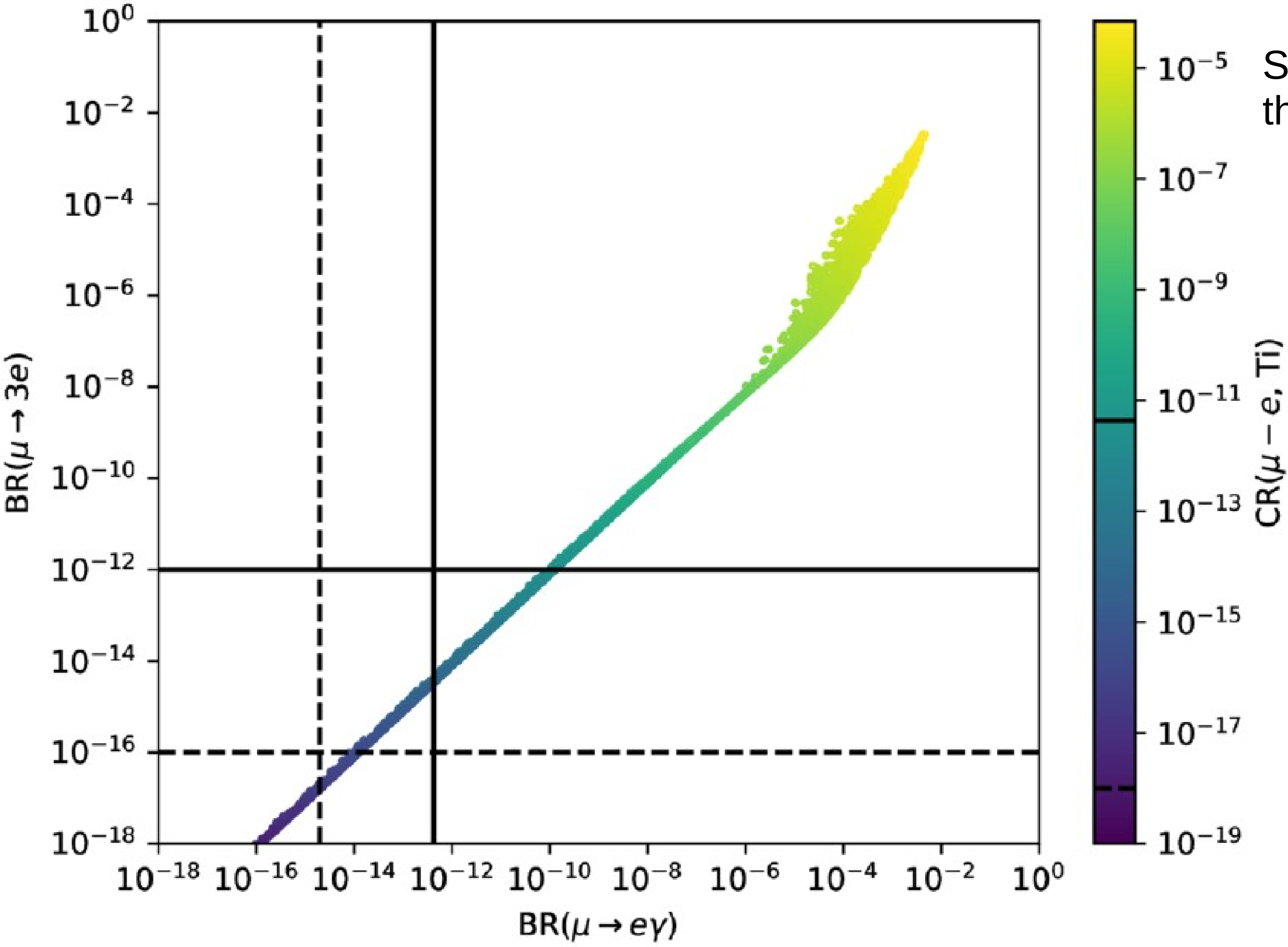
Left hand side can be written as **diag(0,1,1) =** $\boldsymbol{R^\dagger R}$ with R a rotation matrix:

$$R = \begin{pmatrix} 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \Rightarrow R = M^{1/2} \lambda_8 U_\nu D_\nu^{-1/2}$$

Inverting this relation we obtain an expression for the coupling in terms of the other quantities:

$$\boxed{\lambda_8 = M^{-1/2} R D_\nu^{1/2} U_\nu^\dagger}$$

Lepton flavour violation constrains



Strong correlation between three processes

SINDRUM collaboration:
Nucl.Phys. B 299 (1988) 1

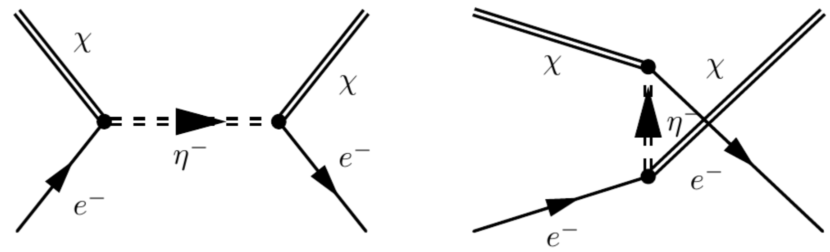
Similar sensitivity as in MEG will be reached in the future by the other experiments.

SINDRUM II collaboration:
Phys. Lett. B 317 (1993) 631

Electron recoil sensitivity study

LFV sets strong constrains on the couplings to leptons.

Nevertheless we expect some signal from electron recoil.



Ionization rate:

$$\frac{dR_{\rm ion}}{d\ln E_{\rm er}} = N_{\rm T}\frac{\rho_\chi}{m_\chi}\sum_{n\ell}\frac{d\langle\sigma_{\rm ion}^{n\ell}v\rangle}{d\ln E_{\rm er}}$$

N_T : # target nuclei per unit mass

ρ_χ = 0.4 GeV/cm^3 : local DM density

J.I. Read: **J. Phys. G 41 (2014) 063101**

Thermally averaged differential cross section:

$$\frac{d\langle\sigma_{\rm ion}^{n\ell}v\rangle}{d\ln E_{\rm er}} = \boxed{\frac{\bar\sigma_{\chi e}}{8\mu_{\chi e}^2}}\int \boxed{|f_{\rm ion}^{n\ell}(k',q)|^2 F(k',Z_{\rm eff})}|F_{\rm DM}(q)|^2\boxed{\eta(v_{\rm min},t)}\; q\; dq$$

$$\boxed{\left|f_{\rm ion}^{n\ell}(k',q)\right|^2 = \frac{(2\ell+1)k'^2}{4\pi^3 q}\int\left|\chi_{n\ell}(k)\right|^2 kdk}$$

$$\boxed{F(k',Z_{\rm eff}) = \frac{2\pi\nu}{1-e^{-2\pi\nu}} \quad \text{with} \quad \nu = Z_{\rm eff}\frac{\alpha m_e}{k'}}$$

χ_{nl} : radial part of momentum space wave function of bound electron

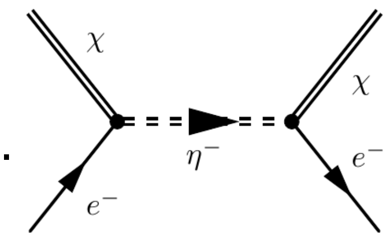
Z_{eff} : effective charge felt by the electron (Z_{eff} = 1)

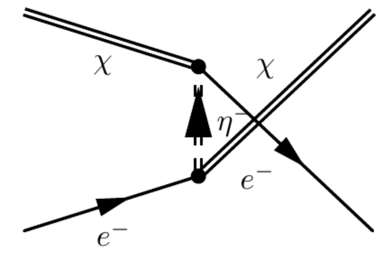
(Assuming target electrons as single-particles states of isolated atoms, we can use numerically tabulated Roothaan-Hartree-Fock wave functions)

Electron recoil sensitivity study

LFV sets strong constrains on the couplings to leptons.

Nevertheless we expect some signal from electron recoil.





Ionization rate:

$$\frac{dR_{\mathrm{ion}}}{d\ln E_{\mathrm{er}}} = N_{\mathrm{T}} \frac{\rho_\chi}{m_\chi} \sum_{n\ell} \frac{d\langle \sigma_{\mathrm{ion}}^{n\ell} v\rangle}{d\ln E_{\mathrm{er}}}$$

N_T : # target nuclei per unit mass

ρ_χ = 0.4 GeV/cm^3 : local DM density

J.I. Read: **J. Phys. G 41 (2014) 063101**

Thermally averaged differential cross section:

$$\frac{d\langle \sigma_{\mathrm{ion}}^{n\ell} v\rangle}{d\ln E_{\mathrm{er}}} = \boxed{\frac{\bar{\sigma}_{\chi e}}{8\mu_{\chi e}^2}} \int \boxed{|f_{\mathrm{ion}}^{n\ell}(k', q)|^2 F(k', Z_{\mathrm{eff}})} |F_{\mathrm{DM}}(q)|^2 \boxed{\eta(v_{\mathrm{min}}, t)}\, q\, dq$$

$$\boxed{\eta(v_{\mathrm{min}}, t) = \int_{v_{\mathrm{min}}}^{\infty} \frac{d^3 v}{v} f(\mathbf{v}, t)}$$

$$\boxed{f_\infty(\mathbf{v}) = 1/N_{\mathrm{esc}} (\pi v_0^2)^{-3/2} e^{-\mathbf{v}^2/v_0^2}, \quad \text{if} \quad |\mathbf{v}| \leq v_{\mathrm{esc}}}$$

$$\boxed{v_{\mathrm{min}} = \frac{E_{\mathrm{B}}^{n\ell} + E_{\mathrm{er}}}{q} + \frac{q}{2m_\chi}}$$

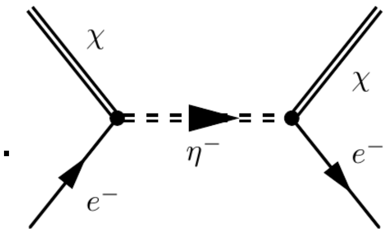
E_B : binding energy
E_{er} : recoil energy

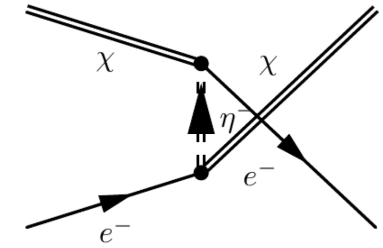
Local circular velocity : v_0 = 220 km/s
Escape velocity : v_{esc} = 544 km/s

Electron recoil sensitivity study

LFV sets strong constrains on the couplings to leptons.

Nevertheless we expect some signal from electron recoil.





Ionization rate:

$$\frac{dR_{\rm ion}}{d\ln E_{\rm er}} = N_{\rm T}\frac{\rho_\chi}{m_\chi}\sum_{n\ell}\frac{d\langle\sigma^{n\ell}_{\rm ion}v\rangle}{d\ln E_{\rm er}}$$

N_T : # target nuclei per unit mass

ρ_χ = 0.4 GeV/cm^3 : local DM density

J.I. Read: **J. Phys. G 41 (2014) 063101**

Thermally averaged differential cross section:

$$\frac{d\langle\sigma^{n\ell}_{\rm ion}v\rangle}{d\ln E_{\rm er}} = \boxed{\frac{\bar\sigma_{\chi e}}{8\mu^2_{\chi e}}}\int \boxed{|f^{n\ell}_{\rm ion}(k',q)|^2 F(k',Z_{\rm eff})}|F_{\rm DM}(q)|^2\boxed{\eta(v_{\rm min},t)}\; q\; dq$$

$$\boxed{\bar\sigma_{\chi e} = \frac{\mu^2_{\chi e}}{16\pi m^2_\chi m^2_e}\overline{|\mathcal{M}_{e\chi}(q)|^2}\Big|_{q^2=\alpha^2 m^2_e}}$$

Non-relativistic reference cross section at fixed momentum transfer

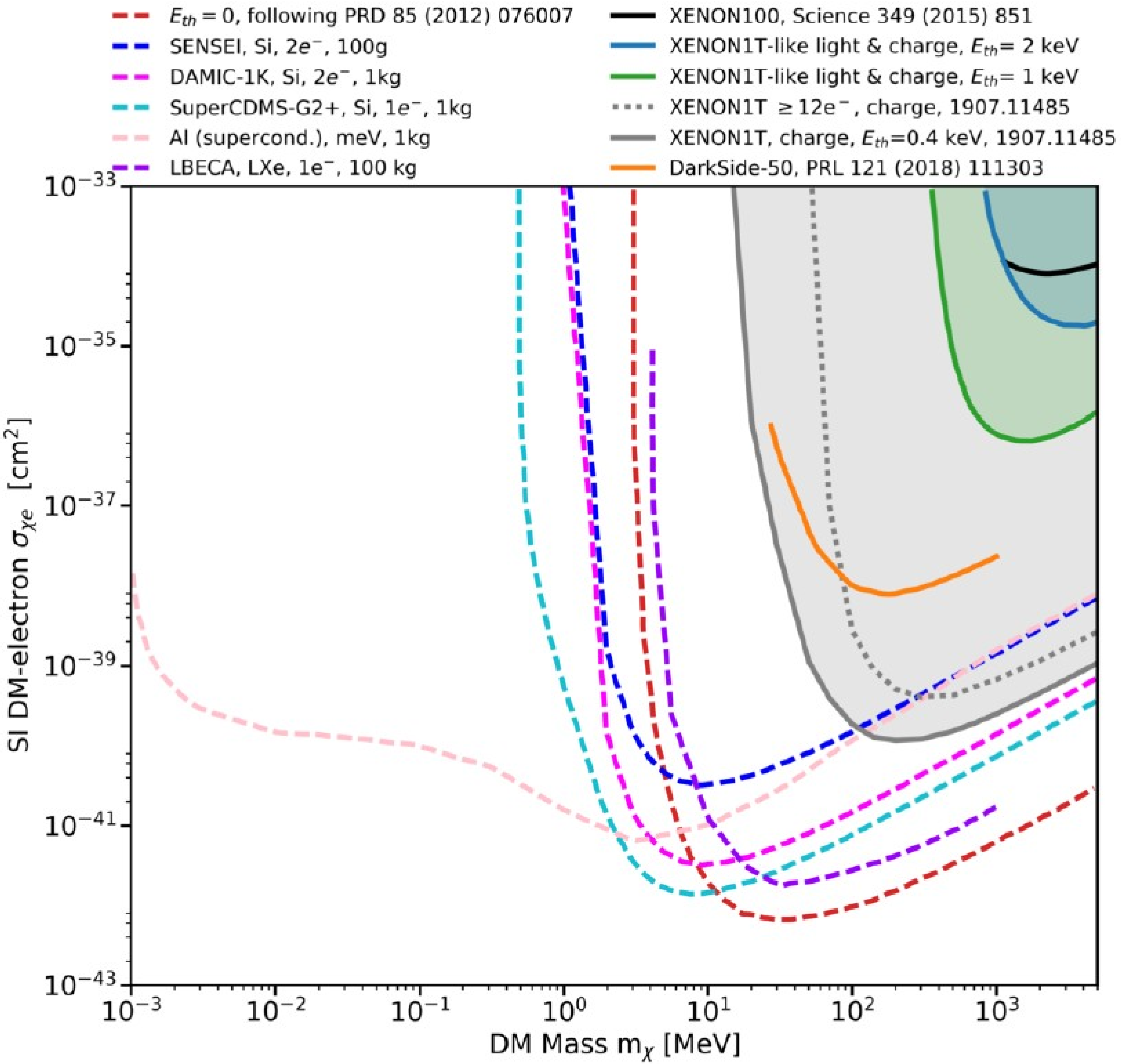
$$\boxed{|F_{\rm DM}(q)|^2 = \overline{|\mathcal{M}_{e\chi}(q)|^2}/\overline{|\mathcal{M}_{e\chi}(\alpha m_e)|^2}}$$

Form factor captures the *q*-dependence of the matrix element

$$\boxed{\bar\sigma_{\chi e} = \frac{\mu^2_{\chi e}(\lambda^{e1}_8)^4}{\pi m^4_{\eta^\pm}}}$$

For heavy mediators we can assume F_{DM} = 1 and integrate out the propagator

Electron recoil sensitivity study



XENON novel analysis exploiting only S2 signal with low energy threshold at most few times 10^{-41} cm^2

(several strong assumptions on dector threshold and background)