Gauge U(1)<sub>D</sub> Symmetry for ALRM

Oleg Popov

#### RLM

Introduction MLRM ALRM U(1) $_{o}$  Gauged ALRM Constraints on the U(1) $_{o}$ ALRM Conclusions

Scotogenic Inverse Seesaw Model of Particle Content Relevant Lagrangian Terms Neutrino Mass Neutrino Mass Generation Mixing of

## Dark Gauge U(1) Symmetry for an Alternative Left-Right Model

### Oleg Popov

University of California, Riverside

opopo001@ucr.edu

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In collaboration with Sean Fraser, Corey Kownacki, Ernest Ma, Nicholas Pollard, Mohammadreza Zakeri

### Overview

#### Gauge U(1)<sub>D</sub> Symmetry for ALRM

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DLRM

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Neutrino Mass Generation

Mixing of

#### $m_{\nu}$

### 1 Left-Right Models

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- Alternative Left-Right Model
- Dark Alternative Left-Right Models with Global Symmetries
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  - Model
    - Particle Content
    - Relevant Lagrangian Terms
  - Neutrino Mass
    - Neutrino Mass Generation
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### Introduction/Motivation

#### Gauge U(1)<sub>D</sub> Symmetry for ALRM

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Scotogenic Inverse Seesaw Model of Particle Content Relevant Lagrangian Terms Neutrino Mass Neutrino Mass Generation Mixing of Restore symmetry between Left-Right sectors

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- Generate naturally small neutrino masses
- Accomodate dark matter

### Minimal Left-Right Model

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Conclusions

Scotogenic Inverse Seesaw Model of Particle Content Relevant Lagrangian Terms Neutrino Mass Generation Mixing of

- Simple extention of the SM gauge group
- Spontaneous/Explicit breaking of P (SU(2)<sub>L</sub> ←→SU(2)<sub>R</sub>) (also CP)
- Genartion of naturaly light neutrino masses (Seesaw I/III)

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\begin{split} & \mathcal{Q}_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \equiv [3,2,1,\frac{1}{3}] \quad \mathcal{Q}_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \equiv [3,1,2,\frac{1}{3}] \\ & \ell_L = \begin{pmatrix} v_L \\ e_L \end{pmatrix} \equiv [1,2,1,-1] \quad \ell_R = \begin{pmatrix} v_R \\ e_R \end{pmatrix} \equiv [1,1,2,-1]. \quad \ast \end{split}$$

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- $\eta \sim (1,2,2,0), \Delta_L \sim (1,3,1,-1), \Delta_R \sim (1,1,3,-1)$ • Seesaw I/II
- $\eta \sim (1,2,2,0), \phi_L \sim (1,2,1,1/2), \phi_R \sim (1,1,2,1/2)$
- Double seesaw through Weinberg dim-5 operator
- Flavour changing neutral currents
- \*N.G. Deshpande et al., Phys. Rev. D 44, 837 (1991).

### Alternative Left-Right Model

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$$\begin{aligned} \mathsf{SU}(3)_C \times \mathsf{SU}(2)_L \times \mathsf{SU}(2)_R \times \mathsf{U}(1)_{B-L} \\ & (u,d)_L : (3,2,1,\frac{1}{6}) \quad (h^c,u^c)_L : (\bar{3},1,2,-\frac{1}{6}) \\ & (\nu_E,E)_L : (1,2,1,-\frac{1}{2}) \quad (e^c,n)_L : (1,1,2,\frac{1}{2}) \\ & h_L : (3,1,1,-\frac{1}{3}) \quad d_L^c : (\bar{3},1,1,\frac{1}{3}) \\ & \left( \begin{matrix} \nu_e & E^c \\ e & N_E^c \end{matrix} \right)_L : (1,2,2,0) \qquad N_L^c : (1,1,1,0), \end{aligned}$$

- ALRM is motivated by superstring-inspired E<sub>6</sub> model
- Flavour changing neutral currents are naturally absent tree level
- W<sup>±</sup><sub>R</sub> has lepton number ±1 and odd parity so they do not mix with W<sup>±</sup><sub>L</sub>
- SU(2)<sub>R</sub> breaking scale can be below as TeV, W<sup>±</sup><sub>R</sub> and Z' are reachiable at LHC

<sup>†</sup>E. Ma, Phys. Rev. D 36, 274 (1987); K. S. Babu, X.-G. He, and

E. Ma, Phys. Rev. D 36, 878 (1987); J. L. Hewett and T. G. Rizzo, 4/23

### Dark Alternative Left-Right Models with Global Symmetries

Fermion	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$	S	Scalar	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(2)_R$
$\psi_L = (\nu, e)_L$	(1, 2, 1, -1/2)	1	Φ	(1, 2, 2, 0)
$\psi_R = (n, e)_R$	(1, 1, 2, -1/2)	1/2	$\tilde{\Phi} = \sigma_2 \Phi^* \sigma_2$	(1, 2, 2, 0)
$Q_L = (u, d)_L$	(3, 2, 1, 1/6)	0	$\Phi_L$	(1, 2, 1, 1/2)
$Q_R = (u, h)_R$	(3, 1, 2, 1/6)	1/2	$\Phi_R$	(1, 1, 2, 1/2)
$d_R$	(3, 1, 1, -1/3)	0	$\Delta_L$	(1, 3, 1, 1)
$h_L$	(3, 1, 1, -1/3)	1	$\Delta_R$	(1, 1, 3, 1)

- No tree level FCNC
- Neutrino masses(m $_{\nu} \sim \left< \Delta_L^0 \right> \implies L \rightarrow (-1)^L$ , R parity)
  - Fermionic Dark Matter (Scotinos) (m<sub>n</sub>  $\sim \left< \Delta_R^0 \right>$ )
  - Lepton number given by L=S-T<sub>3R</sub>

• 
$$\langle \phi_1^0 \rangle = 0$$
 by S-T<sub>3R</sub>

- h,  $W_R^{\pm}$  has L=1, $\mp 1$
- SM particles are even, n, h, W<sup>±</sup><sub>R</sub>, and Δ<sup>±</sup><sub>R</sub> are odd under parity

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<sup>‡</sup>S. Khalil, H.-S. Lee, E. Ma, Phys. Rev. D 79, 041701(R) (2009)

#### Gauge U(1)<sub>D</sub> Symmetry for ALRM

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#### DLRM

U(1)<sub>D</sub> Gauged ALRM

Constraints of the U(1)<sub>D</sub> ALRM

Scotogenic Inverse Seesaw Model of Neutrino Mass

- Model
- Particle

Relevant

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Neutrino Mas Generation

Mixing of

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### Dark Alternative Left-Right Models II with Global Symmetries

Fermion	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$	S			
$\psi_L = (\nu, e)_L$	(1, 2, 1, -1/2)	1			
$\psi_R = (n, e)_R$ $\nu_R$	(1, 1, 2, -1/2) (1, 1, 1, 0)	3/2			
nL	(1, 1, 1, 0)	2	Scalar	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)$	
$Q_L = (u, d)_L$	(3, 2, 1, 1/6)	0	Φ	(1, 2, 2, 0)	-1
$Q_R = (u, h)_R$	(3, 1, 2, 1/6)	-1/2	$\Phi = \sigma_2 \Phi^* \sigma_2$	(1, 2, 2, 0)	1,
$d_R$	(3, 1, 1, -1/3)	0	$\Phi_L$	(1, 2, 1, 1/2)	
hL	(3, 1, 1, -1/3)	-1	$\Phi_R$	(1, 1, 2, 1/2)	1

- No tree level FCNC
- Dirac neutrino masses(m $_{\nu} \sim \left\langle \phi_{L}^{0} \right\rangle$ )
- Dirac Fermionic Dark Matter (Scotinos) (m<sub>n</sub> ~  $\langle \phi_R^0 \rangle$ )
- Lepton number given by  $L=S+T_{3R}$  and is conserved

• 
$$\left< \phi_1^0 \right> = 0$$
 by S+T<sub>3R</sub>

- $\nu_R \nu_R$  breaks L and generates Majorana neutrino mass through canonical seesaw
- *n* remains Dirac fermion protected by residual global U(1) (*n*, W<sup>+</sup><sub>R</sub> ~1, h,  $\phi_1^{0,-}$  ~-1)
- <sup>§</sup>S. Khalil, H.-S. Lee, E. Ma, Phys. Rev. D 81, 051702(R) (2010)

Gauge U(1)<sub>D</sub> Symmetry for ALRM

DLRM

### Particle Content of the $U(1)_D$ ALRM

Gauge U(1) o						
Symmetry for	particles	$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_X$	$U(1)_S$
ALRM	$(u,d)_L$	3	2	1	1/6	0
Oleg Popov	$(u,h)_R$	3	1	2	1/6	-1/2
	$d_R$	3	1	1	-1/3	0
RLM	$h_L$	3	1	1	-1/3	-1
	$(\nu, l)_L$	1	2	1	-1/2	0
	$(n, l)_R$	1	1	2	-1/2	1/2
	$\nu_R$	1	1	1	0	0
$U(1)_D$ Gauged	$n_L$	1	1	1	0	1
Constraints on	$(\phi^+_L,\phi^0_L)$	1	2	1	1/2	0
	$(\phi_R^+,\phi_R^0)$	1	1	2	1/2	1/2
	η	1	2	2	0	-1/2
	ζ	1	1	1	0	1
	$(\psi_1^0,\psi_1^-)_R$	1	1	2	-1/2	2
	$(\psi_{2}^{+},\psi_{2}^{0})_{R}$	1	1	2	1/2	1
	$\chi^+_R$	1	1	1	1	-3/2
	$\chi_R^-$	1	1	1	$^{-1}$	-3/2
	$\chi^0_{1R}$	1	1	1	0	-1/2
	$\chi^0_{2R}$	1	1	1	0	-5/2
	σ	1	1	1	0	3
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<sup>¶</sup>C. Kownacki, E. Ma, N. Pollard, OP, M. Zakeri, <u>1706.06501</u>

# Symmetry breaking, Mass Generation, and Flavour Changing Neutral Currents

#### Gauge U(1)<sub>D</sub> Symmetry for ALRM

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#### U(1)<sub>D</sub> Gauged ALRM

Constraints or the U(1)<sub>D</sub> ALRM Conclusions

Scotogenic Inverse Seesaw Model of Neutrino Mass Model Particle Content Relevant Lagrangian Terms

Neutrino Mass Neutrino Mass Generation Mixing of

- $\left<\phi_R^0\right>=0$ ,  $\left<\eta_2^0\right>=0$  and conserve S+T\_{3R}
- All exotic fermions have half integer charges under  $S+T_{3R}$
- Particle content and charge assignments result in additional unbroken Z<sub>2</sub> symmetry, under which exotic ferminons are odd and others are even
- S+T<sub>3R</sub> is broken to S' by  $\langle \sigma \rangle \neq 0$  and gives masses to exotic fermions
- S' charges for exotic fermions are different from S+T<sub>3R</sub> charges
- Presence of ζ induces ζ<sup>3</sup>σ\* and χ<sup>0</sup><sub>1R</sub>χ<sup>0</sup><sub>1R</sub>ζ breakes S' further to Z<sub>3</sub>

### Particle content of proposed model under $(T_{3R} + S) \times Z_2$

particles

Gauge  $U(1)_D$ Symmetry for ALRM

 $U(1)_{D}$  Gauged ALRM

gauge  $T_{3R} + S$  $u, d, \nu, l$ 0 0 1 + $(\phi_L^+, \phi_L^0), (\eta_2^+, \eta_2^0), \phi_R^0$ 0 0 + $n, \phi_R^+, \zeta$ 1 1 +ω  $\omega^2$  $h,(\eta_1^0,\eta_1^-)$ -1 $^{-1}$ + $\psi^+_{2R}, \chi^+_R$ 3/2, -3/20 1 \_  $\psi_{1R}^-, \chi_R^-$ 3/2, -3/20 1 \_  $\psi^0_{1R}, \psi^0_{2R}$ 5/2, 1/2 $\omega, \omega^2$ 1, -1 $\chi^{0}_{1R}, \chi^{0}_{2R}$ -1/2, -5/21, -1 $\omega, \omega^2$ \_ 3 0 1  $\sigma$ +

3

 $\mathbb{Z}_2$ 

 $Z_3$ 

global S'

### Constraints on the $U(1)_D$ ALRM

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- M(Z')>4TeV
- DM candidates: Fermionic DM( $\chi_0$ ) ( $\chi_0 \bar{\chi_0} \implies \zeta \zeta^*$ ), Scalar DM ( $\zeta$ ) ( $\zeta \zeta^* \implies HH$ ) ■  $< \sigma \times v_{rel} >_{\chi} = \frac{f_0^4}{4\pi m_{\chi_0}} \frac{(m_{\chi_0}^2 - m_{\zeta}^2)^{3/2}}{(2m_{\chi_0}^2 - m_{\zeta}^2)^2} (f_0 \zeta \chi_{OR} \chi_{OR})$
- $\bullet < \sigma \times \mathbf{v}_{rel} >_{\zeta} = \frac{\lambda_0^2}{16\pi} \frac{\left(m_{\zeta}^2 m_H^2\right)^{1/2}}{m_{\zeta}^2} \left(\lambda_0 \zeta \zeta^* H H\right)$
- $\nu_R > 35 \, TeV \implies M_{Z'} > 18 \, TeV, M_{W_R} > 16 \, TeV$



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### Conclusions

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Scotogenic Inverse Seesaw Model of Neutrino Mass Model Particle Content Relevant Lagrangian Terms Neutrino Mass Neutrino Mass  (Alternative, Dark)Left-Right Models have no tree level FCNC

Generate naturally small neutrino masses (Seesaw I/II/III/Double)

- Rich phenomenology accessable at LHC
- Different variations are possible
- Natural Dark Matter candidates due to residual symmetry
- 2 layers of DM stabilized by Z<sub>3</sub> and Z<sub>2</sub> in case of Gauged DLRM

### Particle Content of the Model

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Relevant Lagrangian Terms Neutrino Ma

Generation Mixing of

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Particle	<i>SU</i> (3) <sub>C</sub>	$SU(2)_L$	$U(1)_Y$	L	copies	<i>Z</i> <sub>2</sub>
$Q_i = (u, d)_i$	3	2	1/6	0	3	+
и <sup>с</sup>	3*	1	-2/3	0	3	+
$d^c$	3*	1	1/3	0	3	+
$L_i = (\nu, e)_i$	1	2	-1/2	1	3	+
$e^{c}$	1	1	1	-1	3	+
$(E^0, E^-)_{L,R}$	1	2	-1/2	1	1	-
$N_{L,R}$	1	1	0	1	1	-
$\Phi = (\phi^+, \phi^0)$	1	2	1/2	0	1	+
$s_i^0$	1	1	0	0	3	-

### New $\mathcal{L}a$ grangian



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Scotogenic Inverse Seesa Model of Neutrino Ma Model Particle Content

Relevant Lagrangian Terms

Neutrino Mass Neutrino Mass Generation Mixing of  $\mathscr{L}_{new} \supset$ 

$$\overline{N_L} \left( E_R^0 \phi^0 - E_R^- \phi^+ \right) \\ \left( \overline{E_R^0} E_L^0 + E_R^+ E_L^- \right) \\ \left( \overline{\nu_{Li}} E_R^0 + \overline{e_{Li}^-} E_R^- \right) s_j \\ N_L N_L \\ m_i^2 s_i^2$$

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Leptons m<sub>V</sub>

### Scotogenic Neutrino Mass



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 $m_{\nu}$ 

### Mixing of Leptons, $\mathbb{Z}_2$ odd

#### Gauge U(1)<sub>D</sub> Symmetry for ALRM

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$$\mathcal{M}_{E,N} = \begin{pmatrix} 0 & m_E & m_D \\ m_E & 0 & 0 \\ m_D & 0 & m_N \end{pmatrix}$$
$$m_1 = \frac{m_E^2 m_N}{m_E^2 + m_D^2}$$
$$m_{2,3} = \pm \sqrt{m_E^2 + m_D^2} + \frac{m_D^2 m_N}{2 (m_E^2 + m_D^2)}$$
$$m_N \ll m_E, m_D$$

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### Neutrino Mass

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Mixing of Leptons

$m_{\nu} = f^2 \frac{m_D^2 m_N}{m_E^2 + m_D^2} F(x)$
$F(x) = \frac{1}{1-x} \left( 1 + \frac{x \ln x}{1-x} \right)$
$x=rac{m_{s}^{2}}{\left(m_{E}^{2}+m_{D}^{2} ight)}$

$f_{e,\mu, au}$	0.1		
x	pprox 0		
m <sub>N</sub>	10 MeV		
m <sub>D</sub>	10 GeV		
m <sub>E</sub>	1 TeV		
$m_{ u}$	0.1 eV		

### $Z_3$ symmetry and Neutrino Mixing

#### Gauge U(1)<sub>D</sub> Symmetry for ALRM

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$$egin{aligned} (
u_i,l_i) &\sim \underline{1}, \underline{1}', \underline{1}'', \quad s_1 &\sim \underline{1}, \quad (s_2 \pm is_3) \, / \sqrt{2} &\sim \underline{1}', \underline{1}'', \quad l_{iR} &\sim \underline{1}, \underline{1}', \underline{1}'' \ m_s^2 s^2 &+ m_s'^2 \left(s_2^2 + s_3^2\right) \end{aligned}$$

$$\mathcal{M}_{\nu} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & i/\sqrt{2} \\ 0 & 1/\sqrt{2} & -i/\sqrt{2} \end{pmatrix} O^{T} \begin{pmatrix} l(m_{s_{1}}^{2}) & 0 & 0 \\ 0 & l(m_{s_{2}}^{2}) & 0 \\ 0 & 0 & l(m_{s_{3}}^{2}) \end{pmatrix} O \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & i/\sqrt{2} & -i/\sqrt{2} \end{pmatrix}$$

$$\mathcal{M}_{\nu}|_{f_{\mu}=f_{\tau}} = \begin{pmatrix} A & C & C^{*} \\ C & D^{*} & B \\ C^{*} & B & D \end{pmatrix}$$

Cobimaximal Mixing:  $\theta_{23} = \pi/4$ ,  $exp(-i\delta) = \pm i$ ,  $\theta_{13} \neq 0$ 

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 $f_{\mu} \neq f_{\tau}$  case

#### Gauge U(1)<sub>D</sub> Symmetry for ALRM

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$$M_{\nu} = E_{\alpha} U E_{\beta} M_d E_{\beta} U^T E_{\alpha}$$

$$M_{\nu} M_{\nu}^{\dagger} = E_{\alpha} U M_d^2 U^{\dagger} E_{\alpha}^{\dagger}$$

$$M_{\nu}^{\lambda} M_{\nu}^{\lambda \dagger} = E_{\alpha} U \underbrace{\left[1 + \Delta\right] M_{\lambda d}^2 \left[1 + \Delta^{\dagger}\right]}_{OM_{new}^2 O^{\tau}} U^{\dagger} E_{\alpha}^{\dagger}$$

$$\Delta = U^{\dagger} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda - 1 \end{pmatrix} U, \quad M_{\lambda d}^2 = \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & \lambda^2 m_3^2 \end{pmatrix}$$

$$\lambda = \frac{f_{\mu}}{f_{\tau}}$$

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 $f_{\mu} \neq f_{\tau}$  case





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### Muon Anomalous Magnetic Moment

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$$\begin{split} \Delta a_{\mu} &= \frac{(g-2)_{\mu}}{2} = \frac{f_{\mu}^2 m_{\mu}^2}{16\pi^2 m_E^2} \sum_i |U_{\mu i}|^2 \, G(x_i)^{\S} \\ G(x) &= \frac{1-6x+3x^2+2x^3-6x^2 \ln x}{6\left(1-x\right)^4}, \quad x_i = m_{s_i}^2/m_E^2 \\ U &= O \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & i/\sqrt{2} & -i/\sqrt{2} \end{pmatrix} \\ \frac{x_i \ll 1}{m_E \sim 1 \, TeV} \\ \end{split}$$

 $^{\$}\mathsf{S}.$  Kanemitsu and K. Tobe, Phys. Rev. D86, 095025 (2012).

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$$\mu \to e\gamma$$

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$$A_{\mu e} = \frac{e f_{\mu} f_{e} m_{\mu}}{32\pi^{2} m_{E}^{2}} \sum_{i} U_{ei}^{*} U_{\mu i} G(x_{i})$$
$$Br(\mu \to e\gamma) = \frac{12\pi^{2} |A_{\mu e}|^{2}}{m_{\mu}^{2} G_{F}^{2}} < 5.7 \times 10^{-13 \, \ddagger}$$
$$f_{\mu} f_{e} < 0.03$$

<sup>‡</sup>MEG Collaboration, J. Adams et al., Phys. Rev. Lett. 110, 201801 (2013).

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### Dark Matter



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Mixing of

Dark Matter Candidates: NL, S

$$-\mathcal{L}_{int} = rac{\lambda_{hS}}{2} \nu hS^2 + rac{\lambda_{hS}}{4} h^2 S^2$$
  
 $m_S \lesssim m_h/2 \text{ or } m_S > 150 \text{ GeV}$ 

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 $m_{\nu}$ 

### Conclusions

#### Gauge U(1)<sub>D</sub> Symmetry for ALRM

Oleg Popov

#### RLM

Introduction MLRM ALRM DLRM  $U(1)_p$  Gauged ALRM Constraints on the  $U(1)_p$ ALRM Conclusions

Scotogenic Inverse Seesaw Model of Particle Content Relevant Lagrangian Terms Neutrino Mass Generation Mixing of Inverse Seesaw Neutrino Mass

 $\blacksquare$  Z<sub>3</sub> Flavor Symmetry  $\implies$  Cobimaximal Mixing

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- Deviation from Cobimaximal Mixing
- $\blacksquare$  g-2 and  $\mu \to e \gamma$