Neutrino Theory

### Neutrino Theory: Mass, Interactions, Unification

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### Overview

#### Neutrino Theory

- 1 Introduction
- 2 Tree level
- 3 Radiative
- 4 Dirac case
- 5 B-L extension
- 6 Unification
- 7 Connection to GW
- 8 Summary

### Introduction/Motivation

Neutrino Theory

#### Introduction

Tree level

Radiative

Dirac ca

B-L extensio

Unification

Connection to GW

- (Naturally) small neutrino masses
- Connection with dark matter existence
- Lepton mixing
- Unification

#### Standard Model

Neutrino Theory

Introduction

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Radiative

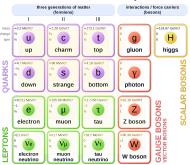
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Unification

GW

Summai

#### Standard Model of Elementary Particles



Gauge symmetry group  $\mathbb{G}_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$ 

$$\mathcal{L}^{Y} = \bar{u}Y_{u}QH + \bar{Q}Y_{d}dH + \text{h.c.}$$
 (1)

$$\langle h^0 \rangle = v \rightarrow m_f = Y_f v$$
 (2)

### Requirements for neutrino mass

Neutrino Theory

#### Introduction

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D-L extensio

Unification

Connection to GW

- Majorana or Dirac type?
- Tree level or radiative?
- New particles? (scalar, fermionic, vector)
- New gauge sectors? (U(1), SU(2), SU(N))

### Possible effects/ Ways to test

Neutrino Theory

#### Introduction

Tree level

Radiativ

Dirac case

B-L extension

Unification

Connection to

- Collider (LHC,ILC, FCC)
- Dark matter
- Grand unified theories
- Neutrino mixing
- Leptogenesis (CPV)
- Neutrinoless N−pole beta decay $(0\nu n\beta)$
- GW via scalar sector

### Tree level, Majorana

Neutrino Theory

Introduction

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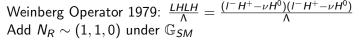
Tree level

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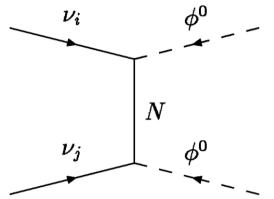
D-L extensi

Unification

Connection to GW



$$\mathcal{L}_{new} = \bar{N} Y_D L H + m_N N_R N_R + \text{h.c.}$$



### Seesaw-I

Neutrino Theory

Introducti

Tree level

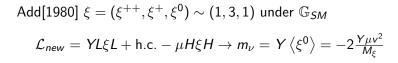
Radiative

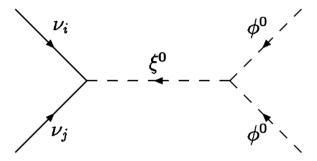
Dirac cas

B-L extension

Unification

Connection to



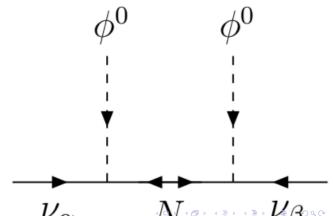


#### Seesaw-III

Neutrino Theory

Tree level

Weinberg Operator 1979:  $\frac{LHLH}{\Lambda} = \frac{(I^-H^+ - \nu H^0)(I^-H^+ - \nu H^0)}{\Lambda}$ Add  $N_R \sim (1, 1, 0)$  under  $\mathbb{G}_{SM}$  $\mathcal{L}_{new} = \bar{\Sigma} Y_D L H + m_N \Sigma_R \Sigma_R + \text{h.c.}$ 



#### Seesaw variations

Neutrino Theory

Introduction

Tree level

Radiative

Dirac cas

R-I extension

Unification

Connection to

GW

$$\mathscr{M}_{\nu N} = \begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix},$$

Seesaw[1979] 
$$m_{
u}=-m_D^2/m_N$$

#### Seesaw variations

Neutrino Theory

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Tree level

Radiative

Dirac cas

R-I extension

Unification

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Connection t GW

Summary

$$\mathcal{M}_{Vn} = \begin{pmatrix} 0 & m_D & 0 \\ m_D & m_1 & m_N \\ 0 & m_N & m_2 \end{pmatrix}$$

Inverse Seesaw[1986]  $m_{
u}=m_{D}^{2}m_{2}/(m_{N}^{2}-m_{1}m_{2})$ 

#### Seesaw variations

Neutrino Theory

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Tree level

Radiative

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Unification

GW

Summary

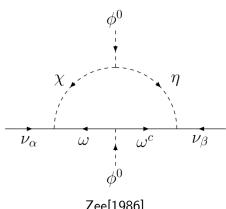
$$\mathcal{M}_{VN} = \begin{pmatrix} 0 & m_D & m_D' \\ m_D & 0 & m_N \\ m_D' & m_N & 0 \end{pmatrix}$$

Linear Seesaw  $m_{\nu} = -2m_D m_{D'}/m_N$ 

### Radiative neutrino mass, Majorana

Neutrino Theory

Radiative



### Radiative neutrino mass, Majorana

Neutrino Theory

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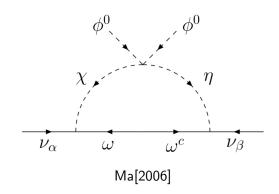
Radiative

Dirac case

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Connection to



### Scotogenic radiative neutrino mass

Neutrino Theory

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Tree level

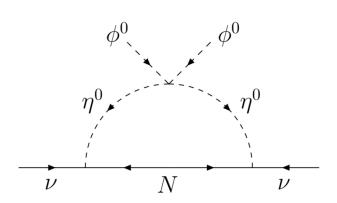
Radiative

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B-L extens

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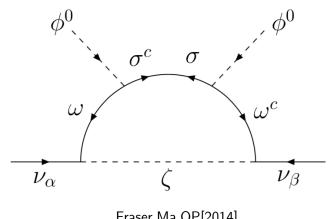


Add  $\mathbb{Z}_2$  symmetry under which  $\eta \sim (1,2,1/2)$  and  $N_R$  are ood

## Radiative neutrino mass, Majorana

Neutrino Theory

Radiative



Fraser, Ma, OP[2014]

### Radiative inverse seesaw neutrino mass, Majorana

Neutrino Theory

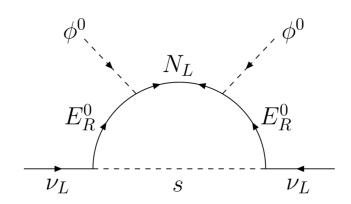
Introduction

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Radiative

Unificatio

Connection to



Add  $\mathbb{Z}_2$  symmetry under which real singlet scalar and  $E_{L,R} \sim (1,2,1/2)$  and  $N_L \sim (1,1,0)$  are odd

#### Dirac neutrinos

Neutrino Theory

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Tree level

Radiative

Dirac case

B-L extension

Unification

Connection to

- Add  $N_R \sim (1,1,0)$  under  $G_{SM}$
- N<sub>R</sub> MUST transfor under some other symmetry non-trivially
- New symmetry *S* is discrete, global, gauged, dark?

#### Tree Dirac case

Neutrino Theory

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Radiative

Dirac case

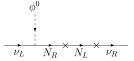
Unification

Offinication

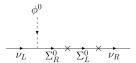
Connection to GW

Summar

• Insert a Dirac fermion singlet N which does not transform under S, then break S softly by the dimension-three  $\bar{\nu}_R N_L$  term.



• Insert a Dirac fermion triplet  $(\Sigma^+, \Sigma^0, \Sigma^-)$  which does not transform under S, then break S and  $SU(2)_L \times U(1)$  together spontaneously to obtain the dimension-three  $\bar{\nu}_R \Sigma_L^0$  term.



#### Dirac case

Neutrino Theory

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Radiative

Dirac case

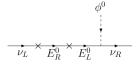
Unification

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Connection to GW

Summary

• Insert a Dirac fermion doublet  $(E^0, E^-)$  which transforms as  $\nu_R$  under S, then break S softly by the dimension-three  $(\bar{E}^0\nu_L + E^+e^-)$  term.



• Insert a scalar doublet  $(\eta^+, \eta^0)$  which transforms as  $\nu_R$  under S, then break S softly by the dimension-two  $(\eta^-\phi^+ + \bar{\eta}^0\phi^0)$  term.



#### Dirac case

Neutrino Theory

Introductio

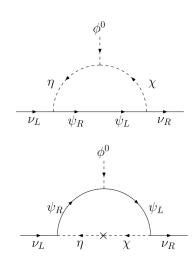
Tree level

Radiative

Dirac case

Unification

Connection to



# $U(1)_{B-L}$ case

Neutrino Theory

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B-L extension

Unification

Connection to GW

- Add 3  $N_R \sim (1, 1, 0)$  which carry L = (1, 1, 1)
- Add 3  $N_R \sim (1,1,0)$  which carry L = (4,4,-5)
- Other variations are possible
- Makes  $U(1)_{B-L}$  anomaly free.
- $U(1)_{B-L}$  can global or gauged
- Global: softly or spontaneously broken(Majorana, Dirac)
- Gauged: spontaneously broken(Majorana, Dirac)

### Scotogenic model in SU(6) GUT\*

Neutrino Theory

Introduction

Tree level

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Unification

Unification

Connection to GW

ummar

Simple case: Extend SU(5) to SU(6) to incude BSM particles needed

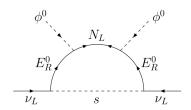
 $\underline{5}_F^* \times \underline{10}_F \times \underline{5}_S^*$ ,  $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$  SU(5) Yukawa terms are extended to

 $\underline{6}_F^* \times \underline{15}_F \times \underline{6}_S^*$ ,  $\underline{15}_F \times \underline{15}_F \times \underline{15}_S$  SU(6) Yukawas Anomaly free combinations:  $5_+^* + 10_F$  for SU(5)

Anomaly free combinations:  $\underline{5}_F^* + \underline{10}_F$  for SU(5),

 $\underline{6}_F^* + \underline{6}_F^* + \underline{15}_F$  for SU(6). New SU(6)  $\underline{21}_S$  scalar is added to obtain 2'nd Higgs doublet  $(\mathbb{Z}_2 \sim -)$  with new interactions

$$\underline{6}_F^* \times \underline{6}_F^* \times \underline{21}_S$$
,  $\underline{15}_S^* \times \underline{15}_S^* \times \underline{21}_S \times \underline{21}_S$ 



## Scotogenic model in SU(7) GUT<sup>†</sup>

Neutrino Theory

Introduction

Tree level

Radiative

Dirac case

B-L extension

Unification

Connection to GW

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Less simple case: Extend SU(5) to SU(7) to incude BSM particles needed  $\underline{5}_F^* \times \underline{10}_F \times \underline{5}_S^*$ ,  $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$  SU(5) Yukawa terms are extended to  $\underline{7}_F^* \times \underline{21}_F \times \underline{7}_S^*$ ,  $\underline{21}_F \times \underline{21}_F \times \underline{35}_S$  SU(7) Yukawas Anomaly free combination for SU(7):  $\underline{7}_F^* + \underline{7}_F^* + \underline{7}_F^* + \underline{21}_F$ . New  $\underline{28}_S$  scalar needed to accomodate  $SU(2)_N$  doublet, with new interactions:  $\underline{7}_F^* \times \underline{7}_F^* \times \underline{28}_S$ ,  $\underline{21}_S^* \times \underline{21}_S^* \times \underline{28}_S \times \underline{28}_S$ 

• Insert a Dirac fermion singlet N which does not transform under S, then break S so by the dimension-three  $\bar{\nu}_R N_L$  term.



### Connection to GW signals

Neutrino Theory

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Radiative

Dirac ca

B-L extension

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Connection to GW

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- Neutrino mass requires new scalars or gauge bosons
- Strong first order phase transition (BSM gauge symmetry)
- Strong first order phase transition gives GW
- Some possible models: LR models, SU(N) scotognic symmetry

### Leptogenesis

Neutrino Theory

Introduction

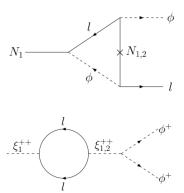
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Radiative

Dirac case

Unification

Connection to



### Summary

Neutrino Theory

Neutrino masses can be Majorana or Dirac

Tree or radiative

Reuire BSM fields and symmetries (globa or gauged)

Connection with DM

Connection with GW

Leptogenesis

Jirac case

B-L extension

Connection to

GW

Summary

# Thank you!