DEPARTMENT OF PHYSICS
MARYLAND CENTER for Fundamental Physics

# Hybrid seesaw leptogenesis and TeV singlets (I)

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based on the work with Kaustubh Agashe, Majid Ekhterachian, Chee Sheng Fong, Sungwoo Hong, Luca Vecchi [arXiv:1804.06847]

# *Outline*

- Standard Type I seesaw and leptogenesis
- Leptogenesis in inverse seesaw
- The hybrid seesaw
- Leptogenesis in hybrid seesaw (see part II)
- Conclusion

# *Problems in SM*

The SM is a good effective model and enjoys a great success in experimental tests

However, there are still several unsolved problems:

- Neutrino mass
- Baryon anti-baryon asymmetry
- Dark matter
- etc.

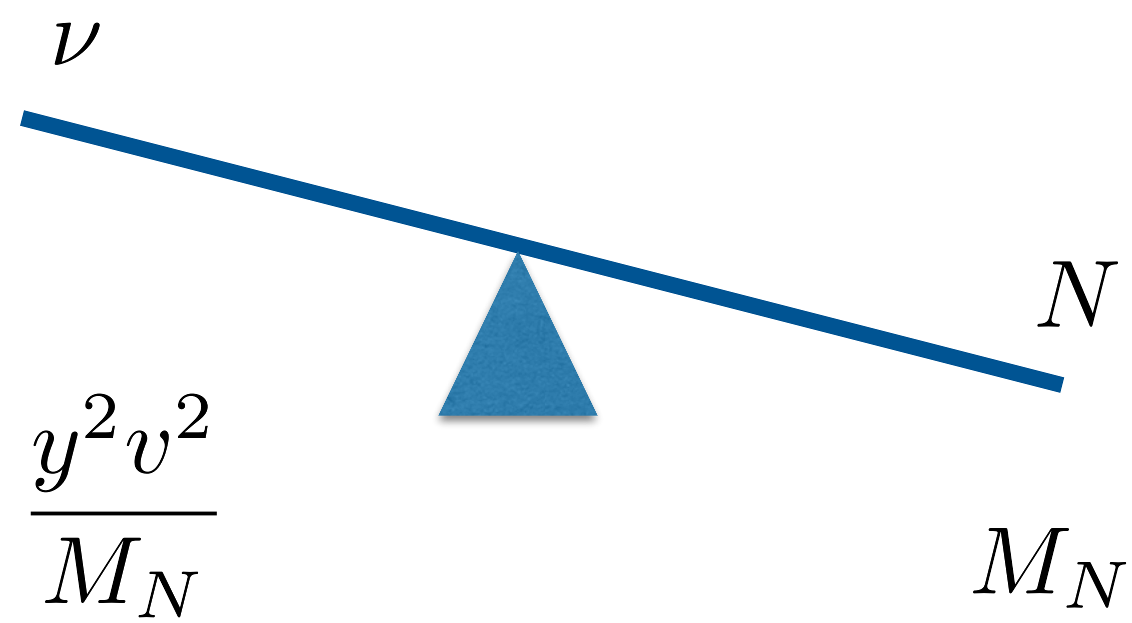
# Neutrino mass and Type I Seesaw Mechanism

[Yanagida,79]
[Gell-Mann, Ramond ,Slansky,79]
[Mohapatra,Senjanovic,80]

$$yNH\ell + M_N NN$$

$$\frac{y^2 \ell H \ell H}{M_N}$$

$$m_\nu \sim \frac{y^2 v^2}{M_N}$$




$$m_\nu \sim 0.1\text{eV} \qquad y \sim 0.1 \qquad M_N \sim 10^{12}\text{GeV}$$

- **Unsuppressed Yukawa couplings**
- **Lepton number is broken at high scale** $M_N$

# Leptogenesis in Type I seesaw

[Fukugita, Yanagida,86]

Asymmetry is generated in leptons and then transferred to baryon asymmetry through sphaleron process.

$$yNH\ell + M_N NN$$

Sakharov three conditions:

- baryon (lepton) number violation
- C and CP violation
- Interactions out of equilibrium

- Majorana mass $M_N$ violates lepton number
- CP phase in $y$
- $N$ decay out of equilibrium

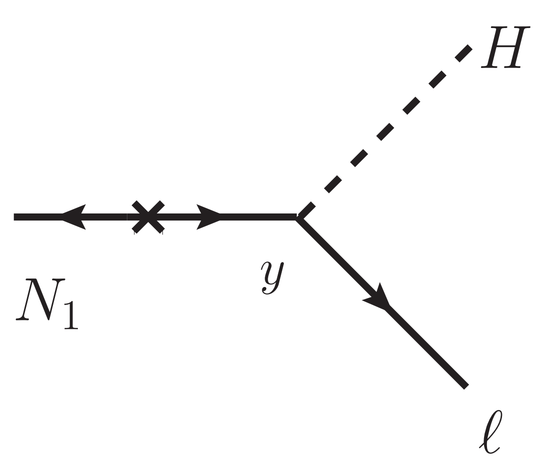
# CP asymmetry

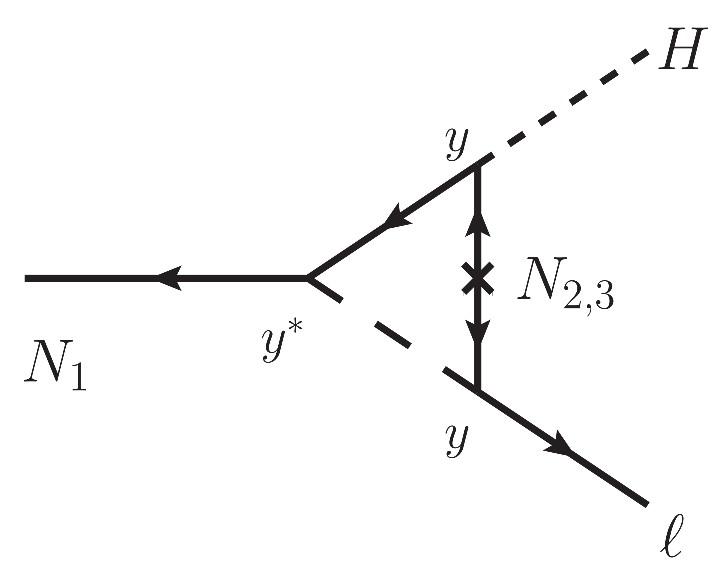
[For a review:Davidson, Nardi,Nir,08]

- CP asymmetry in decay

$$\epsilon = \frac{|\Gamma(N \to \ell H) - \Gamma(N \to \bar{\ell} H^*)|}{\Gamma(N \to \ell H) + \Gamma(N \to \bar{\ell} H^*)}$$

- Need interference between tree and loop diagrams




$$\epsilon \sim \frac{|y|^2}{8\pi} \sim \frac{\Gamma}{M_N}$$

**Assuming no hierarchies in $M_N$ and $y$**

# Lepton asymmetry

Strong washout region: $K \equiv \dfrac{\Gamma}{H(M_N)}$ $\quad K \gg 1$

$T$

$\sim \sqrt{K} M_N$ $\qquad \Gamma = H(T_{\rm eq})$

***N* in eq** $\qquad$ **No net asymmetry**

$M_N$

$\sim \dfrac{M_N}{lnK}$ $\qquad \Gamma e^{-\frac{M_N}{T_{\rm dec}}} = H(T_{\rm dec}) \Rightarrow n_N(T_{\rm dec}) \sim n^{\rm eq} e^{-\frac{m_N}{T_{\rm dec}}} \sim \dfrac{n^{\rm eq}}{K}$

***N* out of eq** $\qquad$ **net asymmetry generated**

$$\frac{n_{\Delta L}}{n^{\rm eq}} \sim \frac{\epsilon}{K}$$

# *Baryon asymmetry*

Sphaleron process: $Y_{\Delta B} \simeq \frac{28}{79} Y_{\Delta L}$

$$Y_X = \frac{n_X}{s}$$

$$Y_{\Delta X} = \frac{n_X - n_{\bar{X}}}{s}$$

Baryon asymmetry:

$$Y_{\Delta B} \simeq \frac{28}{79} \frac{135}{4\pi^4 g_*} \frac{\epsilon}{K} \sim 10^{-3} \frac{\epsilon}{K}$$

$$\epsilon \sim \frac{\Gamma}{M_N} \qquad \Downarrow \qquad K \equiv \frac{\Gamma}{H(M_N)}$$

$$Y_{\Delta B} \sim 10^{-3} \sqrt{g_*} \frac{M_N}{M_{\rm pl}}$$

- Only depend on mass, assuming no hierarchies in $M_N$ and $y$
- To get $Y_{\Delta B}^{\rm obs} \approx 10^{-10}$

  Need $M_N \sim 10^{11} {\rm GeV}$

**close to the seesaw scale!**

# *Pros and cons of high scale Type I seesaw*

Pros:

- A minimal solution to SM neutrino mass
- A viable model for leptogenesis

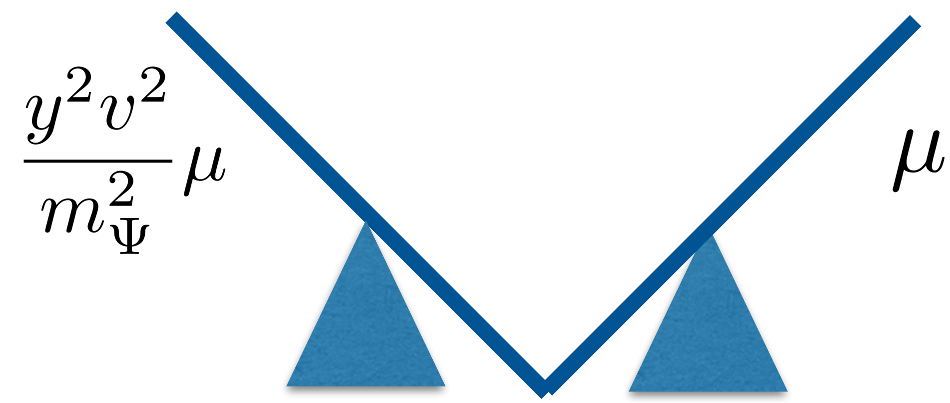
Cons:

- Impossible to probe such heavy singlet neutrinos
- How to generate the seesaw scale? $M_N \sim 10^{12}\mathrm{GeV} \ll M_{\mathrm{pl}}$

# *Inverse seesaw*

**[Mohapatra, 86]**
**[Mohapatra,Valle, 86]**

$$y\Psi^c H\ell + m_\Psi \Psi\Psi^c + \frac{1}{2}\mu\Psi\Psi$$




$\Psi, \Psi^c$ **Pseudo-Dirac**

$$m_\nu \sim \frac{y^2v^2}{m_\Psi^2}\mu$$

$$y \sim 0.1 \quad m_\Psi \sim 1\text{TeV} \quad \mu \sim 1\text{keV}$$

# *Inverse seesaw*

[Mohapatra, 86]
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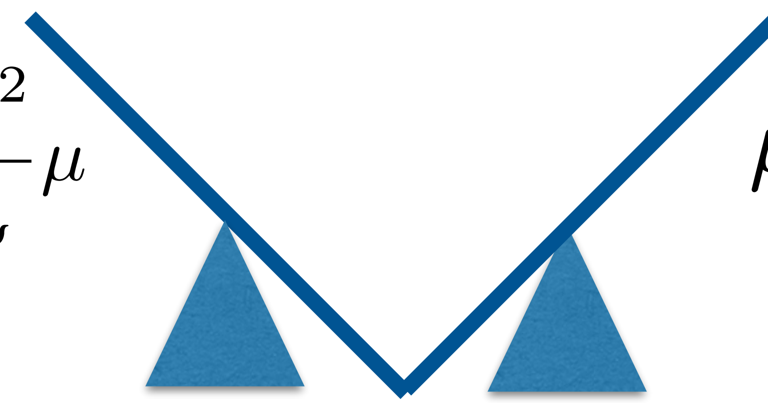


$\frac{y^2v^2}{m_\Psi^2}\mu$ $\mu$

$$m_\nu \sim \frac{y^2v^2}{m_\Psi^2}\mu$$

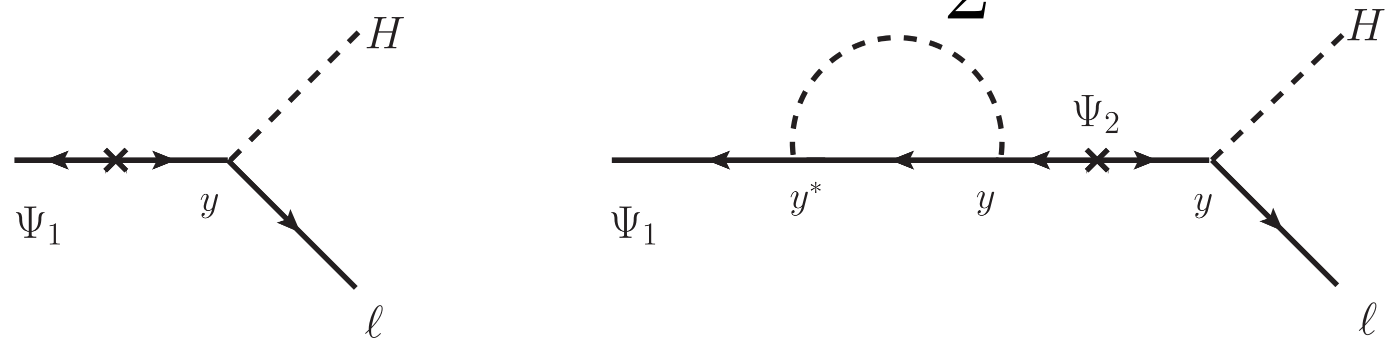
$$y \sim 0.1 \quad m_\Psi \sim 1\text{TeV} \quad \mu \sim 1\text{keV}$$

- ***TeV scale*** **singlet neutrinos with** ***unsuppressed*** **couplings can be probed at colliders**
- **Why $\mu$ is much smaller than TeV scale?**

# CP asymmetry in inverse seesaw

$$y\Psi^c H\ell + m_\Psi \Psi\Psi^c + \frac{1}{2}\mu\Psi\Psi$$

[Deppisch,Pilaftsis, 11]




In mass basis: $$h_i\tilde{\Psi}_i H\ell + \frac{1}{2}m_i\tilde{\Psi}_i\tilde{\Psi}_i$$

$$\frac{m_2 - m_1}{m_1} \sim \frac{\mu}{m_\Psi} \qquad \epsilon_i = \frac{1}{8\pi}\sum_{j\neq i}\frac{\mathrm{Im}[(hh^\dagger)^2_{ij}]}{(hh^\dagger)_{ii}}f_{ij}$$

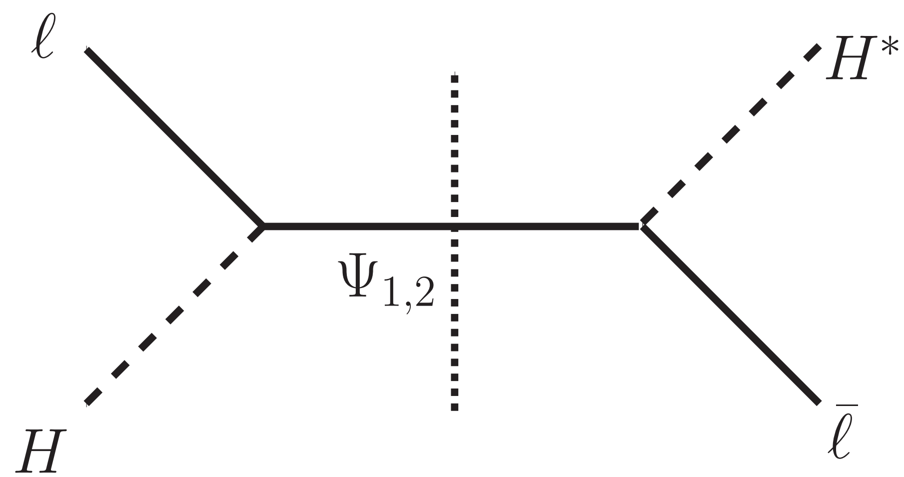
$$\frac{\mathrm{Im}[(h_1h_2^*)]}{|h_1h_2^*|} \sim \frac{\mu}{m_\Psi} \qquad f_{ij} = \frac{(m_i^2 - m_j^2)m_i m_j}{(m_i^2 - m_j^2)^2 + m_i^2\Gamma_j^2}$$

$$\epsilon_1 + \epsilon_2 \sim \frac{\mu}{m_\Psi}\frac{\mu}{\Gamma} \qquad (\mu \ll \Gamma)$$

Yukava Propagator

# *Washout in inverse seesaw*

[Blanchet, Hambye,Josse-Michaux, 11]




$$K^{\text{eff}} = \frac{\Gamma}{H(m_\Psi)} \left(\frac{\mu}{\Gamma}\right)^2$$

- *Vanish as* $\mu \to 0$
- Suppressed compared to original $K$

# Baryon asymmetry in inverse seesaw

CP asymmetry $$\epsilon_1 + \epsilon_2 \sim \frac{\mu}{m_\Psi}\frac{\mu}{\Gamma}$$

Washout $$K^{\rm eff} = \frac{\Gamma}{H(m_\Psi)}\left(\frac{\mu}{\Gamma}\right)^2$$

$$\epsilon \sim \frac{\Gamma}{M_N}$$

$$K = \frac{\Gamma}{H(M_N)}$$

$$Y_{\Delta B} \sim 10^{-3}\sqrt{g_*}\frac{M_N}{M_{\rm pl}}$$

**high scale Type I seesaw**

Baryon asymmetry $$Y_{\Delta B} \sim 10^{-3}\frac{\epsilon}{K}$$ **(strong washout)**

$$Y_{\Delta B} \sim 10^{-3}\sqrt{g_*}\frac{m_\Psi}{M_{\rm pl}} \sim 10^{-18}\frac{m_\Psi}{1{\rm TeV}}$$

**[Agashe,*PD*,Ekhterachian,Fong,Hong,Vecchi,18]**

- The same as high scale Type I seesaw
- ***Too small*** for TeV singlets

# *Pros and cons for inverse seesaw*

Pros:

- TeV scale singlets generate neutrino mass
- Interesting signals at colliders

Cons:

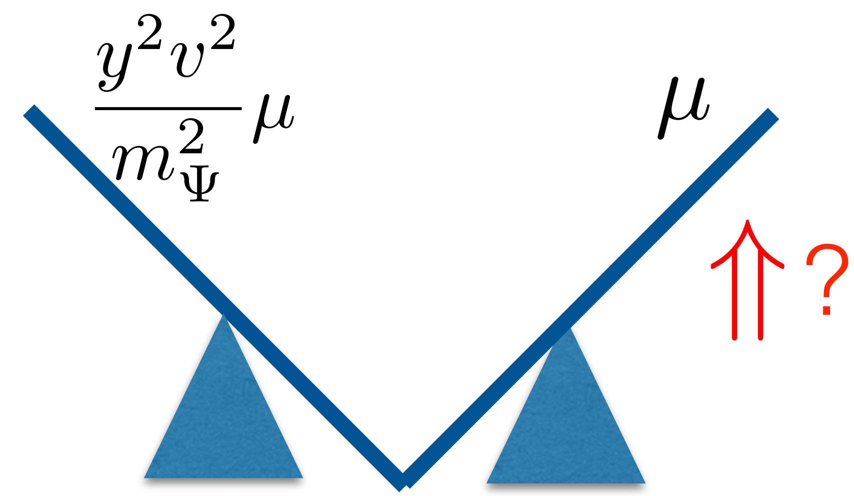
- In tension with leptogenesis

$$Y_{\Delta B} \sim 10^{-3}\sqrt{g_*}\frac{m_\Psi}{M_{\rm pl}} \sim 10^{-18}\frac{m_\Psi}{1{\rm TeV}}$$

- Why $\mu$ (keV) is so small compared to $m_\Psi$ (TeV)?

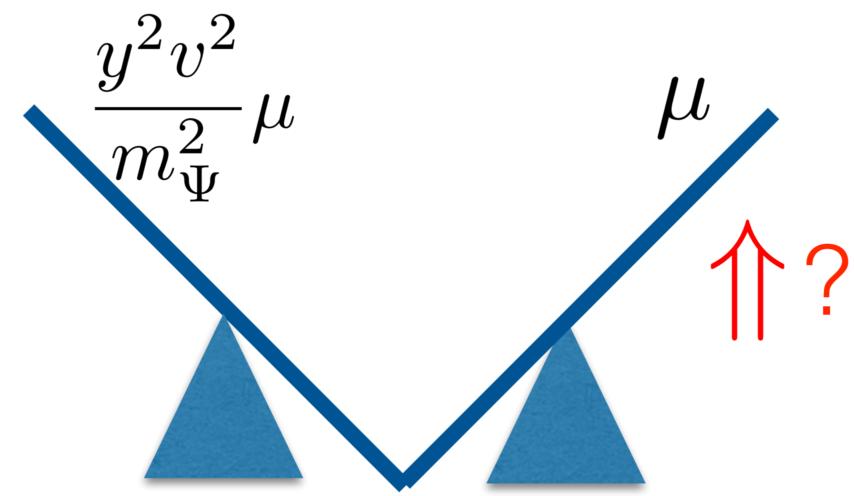
# How to UV complete inverse seesaw?

$$y\Psi^c H\ell + m_\Psi \Psi\Psi^c + \frac{1}{2}\mu\Psi\Psi$$



# *How to UV complete inverse seesaw?*

$$y\Psi^c H\ell + m_\Psi \Psi\Psi^c + \frac{1}{2}\mu\Psi\Psi$$



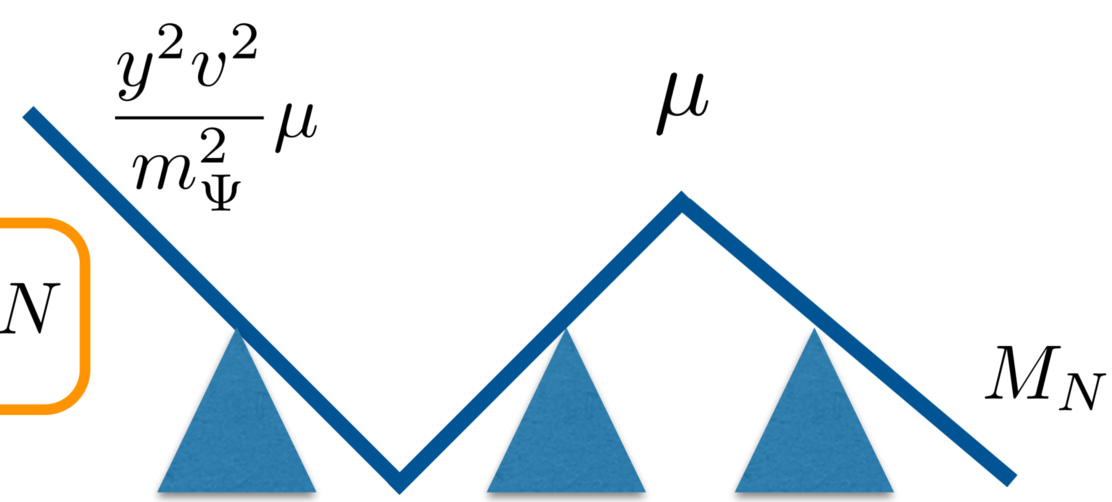

Add a high scale Type I seesaw for $\mu$ !

**Type I seesaw**

$$y\Psi^c H\ell + m_\Psi \Psi^c\Psi + \boxed{\lambda N\Phi_\lambda\Psi + \frac{1}{2}M_N NN}$$

$$\Downarrow$$

$$\mu = \frac{\lambda^2\langle\Phi_\lambda\rangle^2}{M_N}$$



# Hybrid seesaw

[Agashe,*PD*,Ekhterachian,Fong,Hong,Vecchi,18]

$$y\Psi^c H\ell + \kappa\Psi^c\Phi_\kappa\Psi + \lambda N\Phi_\lambda\Psi + \frac{1}{2}M_N NN$$

$y,\kappa,\lambda \gtrsim 0.01$ $\qquad\langle\Phi_\kappa\rangle, \langle\Phi_\lambda\rangle \sim \text{TeV}$ $\qquad M_N \gg \text{TeV}$

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$y, \kappa, \lambda \gtrsim 0.01$ $\quad\langle\Phi_\kappa\rangle, \langle\Phi_\lambda\rangle \sim \mathrm{TeV}$ $\quad M_N \gg \mathrm{TeV}$

Below $M_N$

$$y\ell H\Psi^c + \kappa\Psi^c\Phi_\kappa\Psi + \frac{\lambda^2}{M_N}\Phi_\lambda\Psi\Phi_\lambda\Psi$$

After $\Phi_\kappa\Phi_\lambda$ gets VEV

$$y\Psi^c H\ell + m_\Psi\Psi\Psi^c + \frac{1}{2}\mu\Psi\Psi$$

$m_\Psi = \kappa\langle\Phi_\kappa\rangle$ $\quad\mu = \dfrac{\lambda^2\langle\Phi_\lambda\rangle^2}{M_N}$

# Hybrid seesaw

[Agashe,*PD*,Ekhterachian,Fong,Hong,Vecchi,18]

$$y\Psi^c H\ell + \kappa\Psi^c\Phi_\kappa\Psi + \lambda N\Phi_\lambda\Psi + \frac{1}{2}M_N NN$$

$$y,\kappa,\lambda \gtrsim 0.01 \qquad \langle\Phi_\kappa\rangle, \langle\Phi_\lambda\rangle \sim \mathrm{TeV} \qquad M_N \gg \mathrm{TeV}$$

Below $M_N$

$$y\ell H\Psi^c + \kappa\Psi^c\Phi_\kappa\Psi + \frac{\lambda^2}{M_N}\Phi_\lambda\Psi\Phi_\lambda\Psi$$

After $\Phi_\kappa\,\Phi_\lambda$ gets VEV

$$y\Psi^c H\ell + m_\Psi\Psi\Psi^c + \frac{1}{2}\mu\Psi\Psi$$

$$m_\Psi = \kappa\langle\Phi_\kappa\rangle \qquad \mu = \frac{\lambda^2\langle\Phi_\lambda\rangle^2}{M_N}$$

- All couplings are largish and no new scales below EW scale
- $\mu$ is generated by a high scale seesaw
- Neutrino mass is generated via TeV scale inverse seesaw

# Conclusions

- Leptogenesis in the standard TeV scale inverse seesaw follows a simple formula, which tends to produce *too small* baryon asymmetry

- We study a hybrid seesaw of high scale Type I seesaw and TeV scale inverse seesaw.

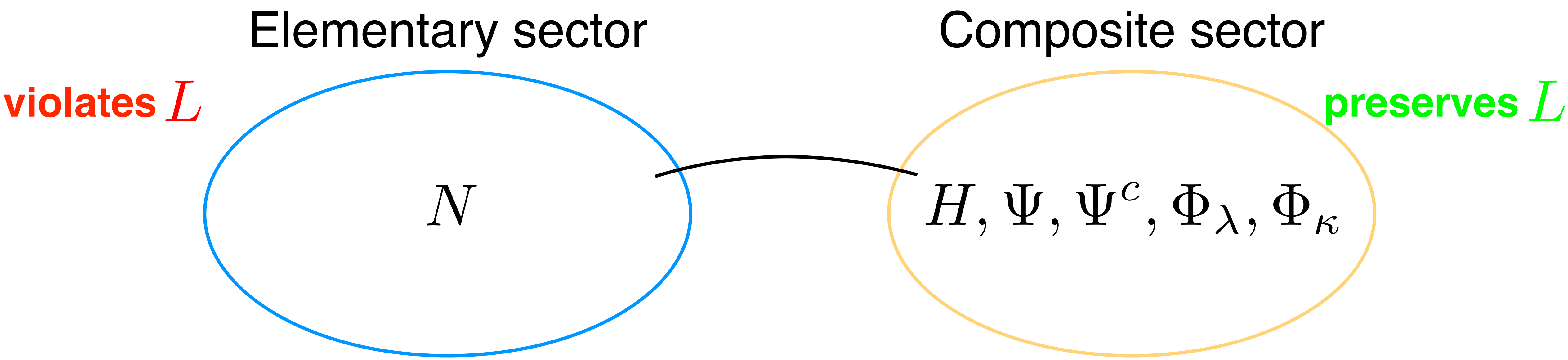
- Hybrid seesaw naturally generating a tiny $\mu$ term via a high scale seesaw

- Hybrid seesaw could achieve successful leptogenesis due to interplay of high scale and TeV scale physics (details are in the next talk).

*Thank you!*

$$y\Psi^c H\ell + \kappa\Psi^c\Phi_\kappa\Psi + \lambda N\Phi_\lambda\Psi + \frac{1}{2}M_N NN$$

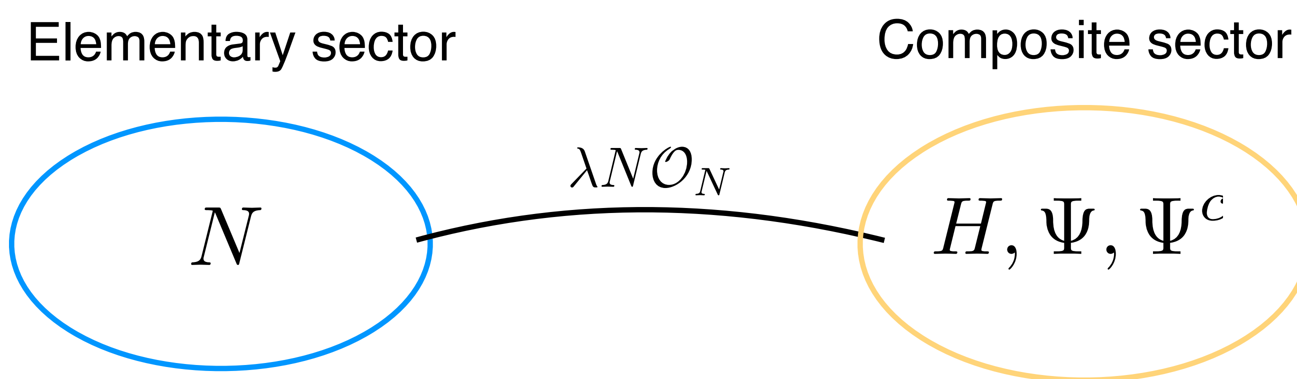
# Toy model for composite seesaw




- Composite/elementary set up forbids other couplings like $y_N NH\ell$
- $V(\Phi_{\kappa,\lambda}, H)$ is generic
- The model has lepton number symmetry in fermions which is broken by $M_N$

# Warped/Composite seesaw

[Agashe, Hong, Vecchi, 15]
[Agashe, *PD*, Hong, 16]
[Agashe, *PD*, Hong, 17]




$$M_{\rm pl} \quad \mathcal{L}_{\rm comp} + \lambda N \mathcal{O}_N + \frac{1}{2} M_N^{\rm UV} N N$$

**RG**

$$\Rightarrow \frac{\lambda^2}{M_N^{\rm UV}} \mathcal{O}_N^2$$

**Confinement (TeV)**

$$y \Psi^c H \ell + m_\Psi \Psi \Psi^c + \frac{1}{2} \mu \Psi \Psi$$

$$m_\psi \sim {\rm TeV}, \mu \sim \frac{{\rm TeV}^2}{M_N^{\rm UV}} \left( \frac{\rm TeV}{M_{\rm Pl}} \right)^{2[\mathcal{O}_N]-5}$$

$$\mu \sim \frac{{\rm TeV}^2}{M_{\rm seesaw}} \quad M_{\rm seesaw} = M_N^{\rm UV} \left( \frac{\rm TeV}{M_{\rm Pl}} \right)^{5-2[\mathcal{O}_N]}$$

- **Only one scale in theory with minimal fields and order one couplings.**
- **Seesaw scale and TeV scale is dynamically generated. No need for additional scalars.**
- **Lepton number is a global symmetry of strong sector and thus forbids *N* direct coupling to Higgs.**
- **Rich collider signatures**
- **It will be very interesting to study leptogenesis in composite sector.**

# Global/gauge symmetries:

$$y\Psi^c H\ell + \kappa\Psi^c\Phi_\kappa\Psi + \lambda N\Phi_\lambda\Psi + \frac{1}{2}M_N NN$$

| | $\ell$ | $\Psi$ | $\Psi^c$ | $\Phi_\kappa$ | $\Phi_\lambda$ |
|---|---|---|---|---|---|
| $U(1)_{B-L}$ | -1 | 0 | 1 | -1 | 0 |
| $U(1)_\Phi$ | 1 | 1 | -1 | 0 | -1 |

- Two U(1) global symmetries forbids other couplings like $y'\Psi H\ell$ which can be embedded in a gauge symmetry
- $V(\Phi_{\kappa,\lambda}, H)$respects global symmetries