Neutrino Mass and the Early Universe

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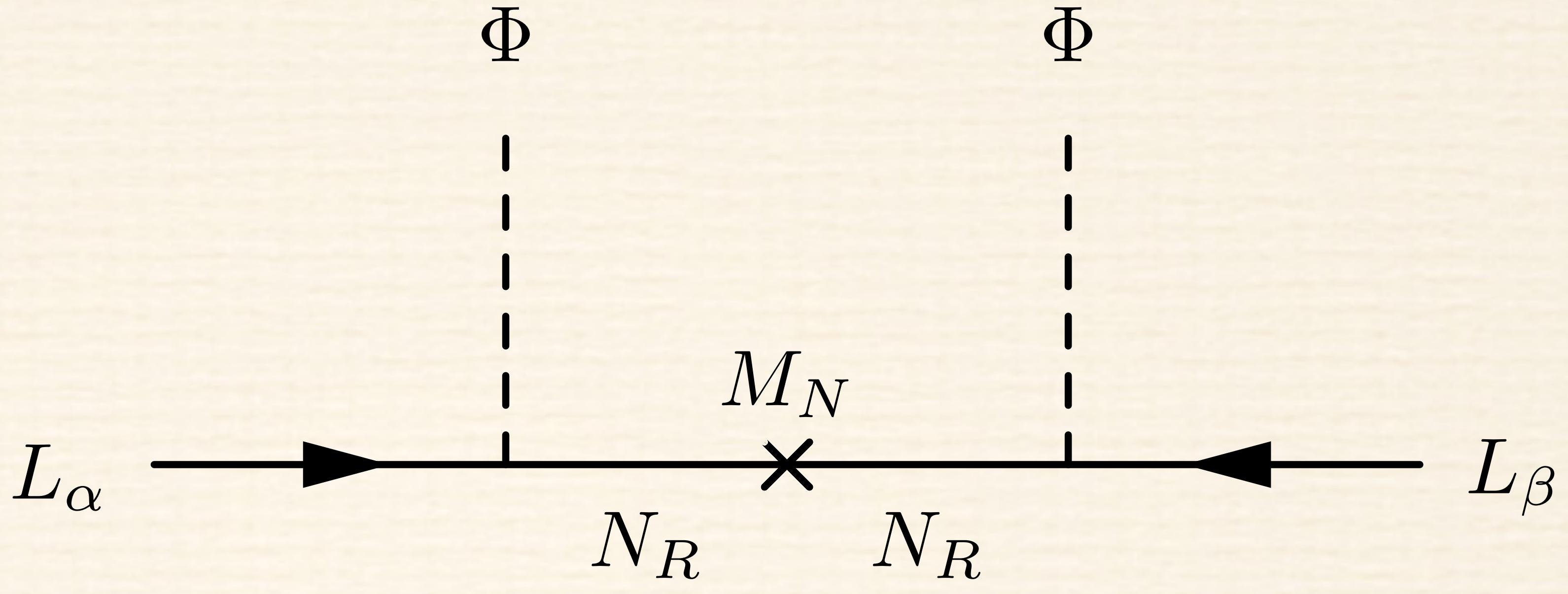
COST CA18108 Second Training School

Outline

- Background on neutrino and cosmology problems
- Neutrino portal dark matter: limitation of type I seesaw model
- Type Ib seesaw model in cosmology

Seesaw Mechanism

- Weinberg operator $\frac{1}{\Lambda}\nu\nu\phi\phi$
- Type I seesaw mechanism $Y\overline{L}\phi N_R$



- Majorana neutrino mass $m \propto \frac{Y^2 v^2}{M_N}$
- Other models: type II, type III, scotogenic, Zee-Babu, …
- The Littlest Seesaw model: a version of type I seesaw model explaining neutrino mass and mixing with two RH neutrinos and minimal free parameters

King JHEP 02 (2016), 085

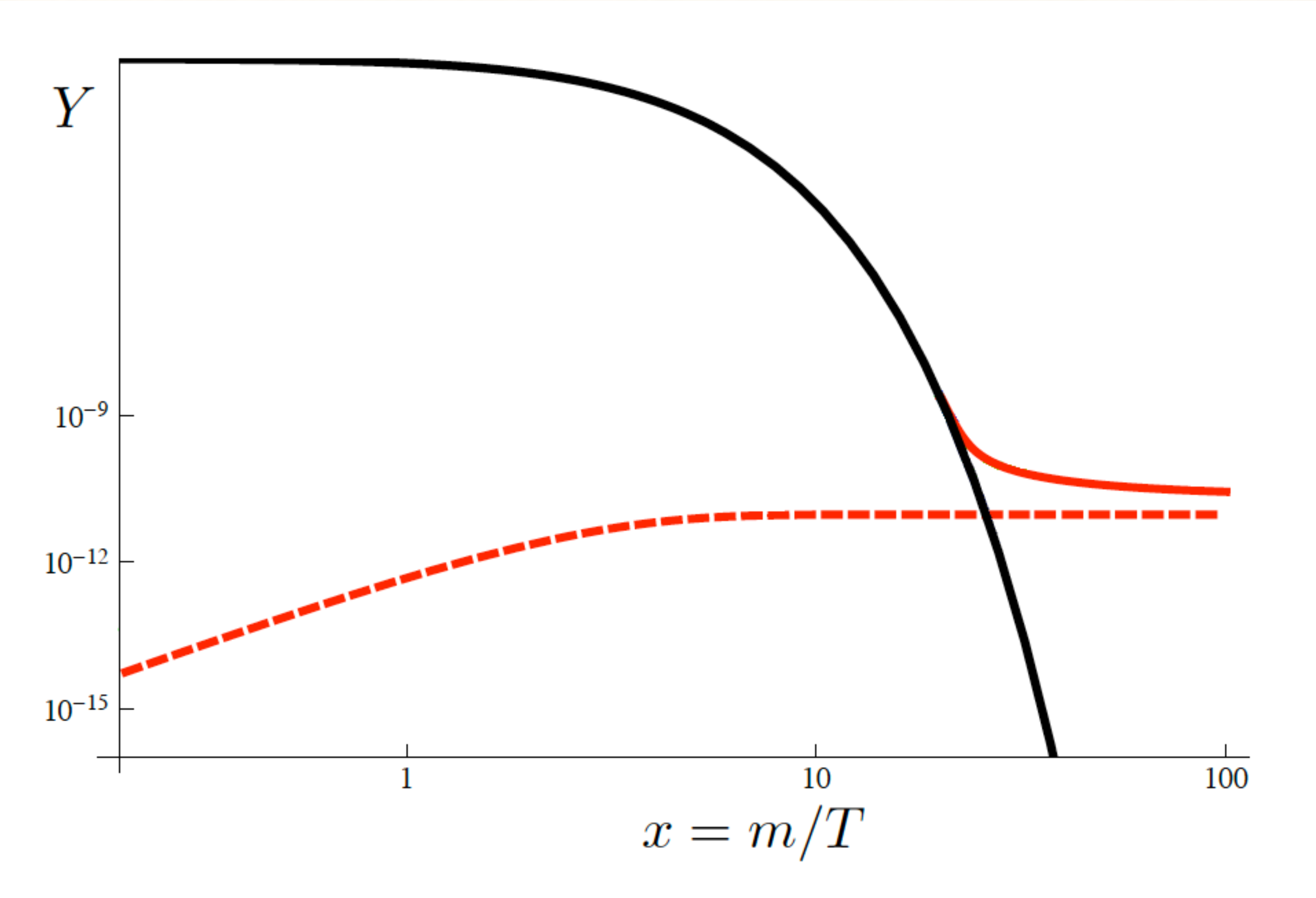
Dark Matter Production

- Boltzmann equation

$$\mathcal{H}\,T\left(1+\frac{T}{3g_*^{\mathfrak{s}}(T)}\frac{dg_*^{\mathfrak{s}}}{dT}\right)^{-1}\frac{dY_i}{dT}=\sum_{kl}\langle\Gamma_{i\to kl}\rangle\,Y_i^{\rm eq}\left(\frac{Y_i}{Y_i^{\rm eq}}-\frac{Y_k\,Y_l}{Y_k^{\rm eq}Y_l^{\rm eq}}\right)-\sum_{jk}\langle\Gamma_{j\to ik}\rangle\,Y_j^{\rm eq}\left(\frac{Y_j}{Y_j^{\rm eq}}-\frac{Y_i\,Y_k}{Y_i^{\rm eq}Y_k^{\rm eq}}\right)$$

$$+\,\mathfrak{s}\sum_{jkl}\langle\sigma_{ij\to kl}\,v_{ij}\rangle\,Y_i^{\rm eq}Y_j^{\rm eq}\left(\frac{Y_i\,Y_j}{Y_i^{\rm eq}Y_j^{\rm eq}}-\frac{Y_k\,Y_l}{Y_k^{\rm eq}Y_l^{\rm eq}}\right)$$

- Freeze-out: The particle is in equilibrium with the thermal bath after reheating. As the universe cools down, the particle decouples from the thermal bath.
- Freeze-in: The particle is out of equilibrium after reheating (usually with negligible initial abundance). The particle is produced gradually from the thermal bath and finally decouples as the universe cools down.

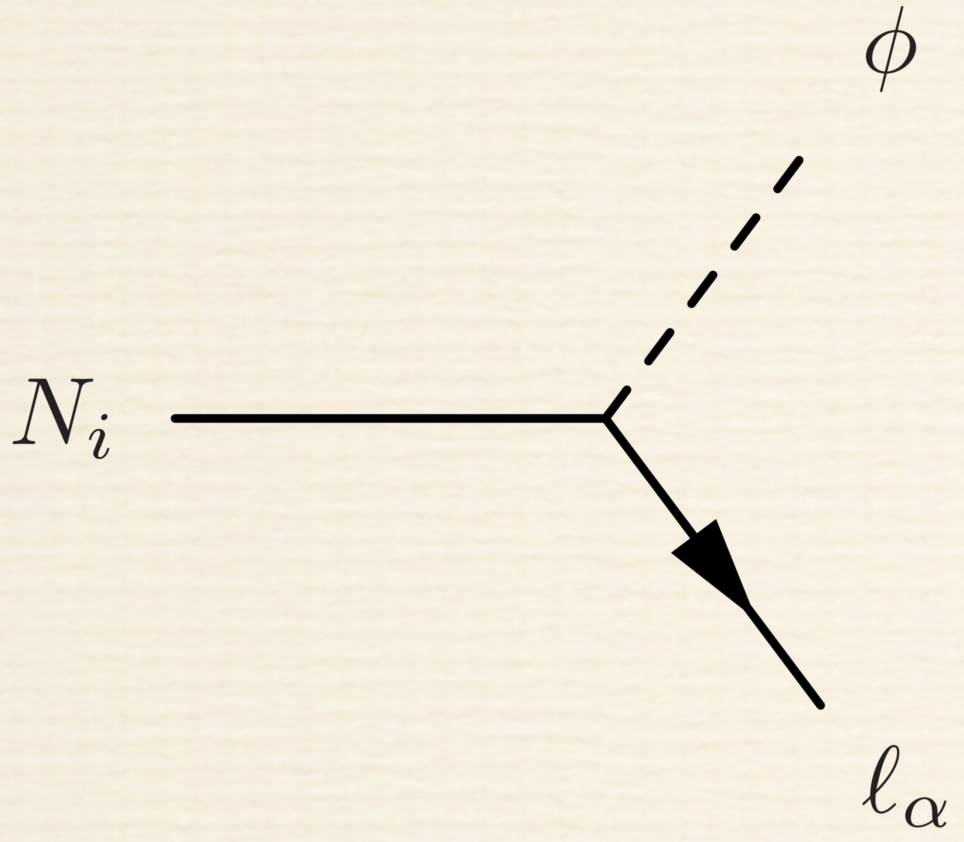


- The observed DM relic abundance gives a constraint $\Omega_{\rm DM}^{\rm obs}h^2=0.120\pm0.001$

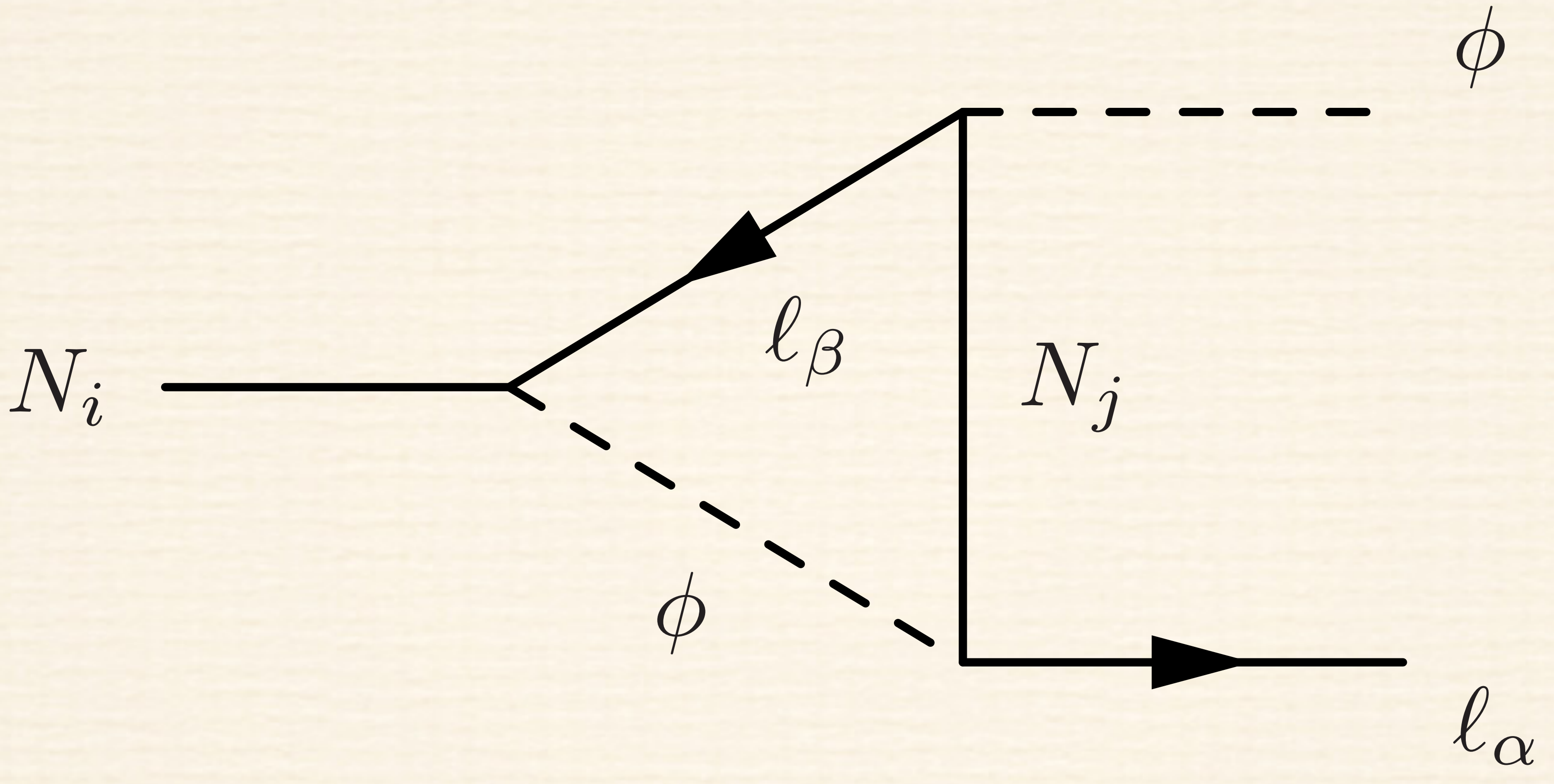
N. Aghanim et al. (Planck), (2018), arXiv:1807.06209

Leptogenesis

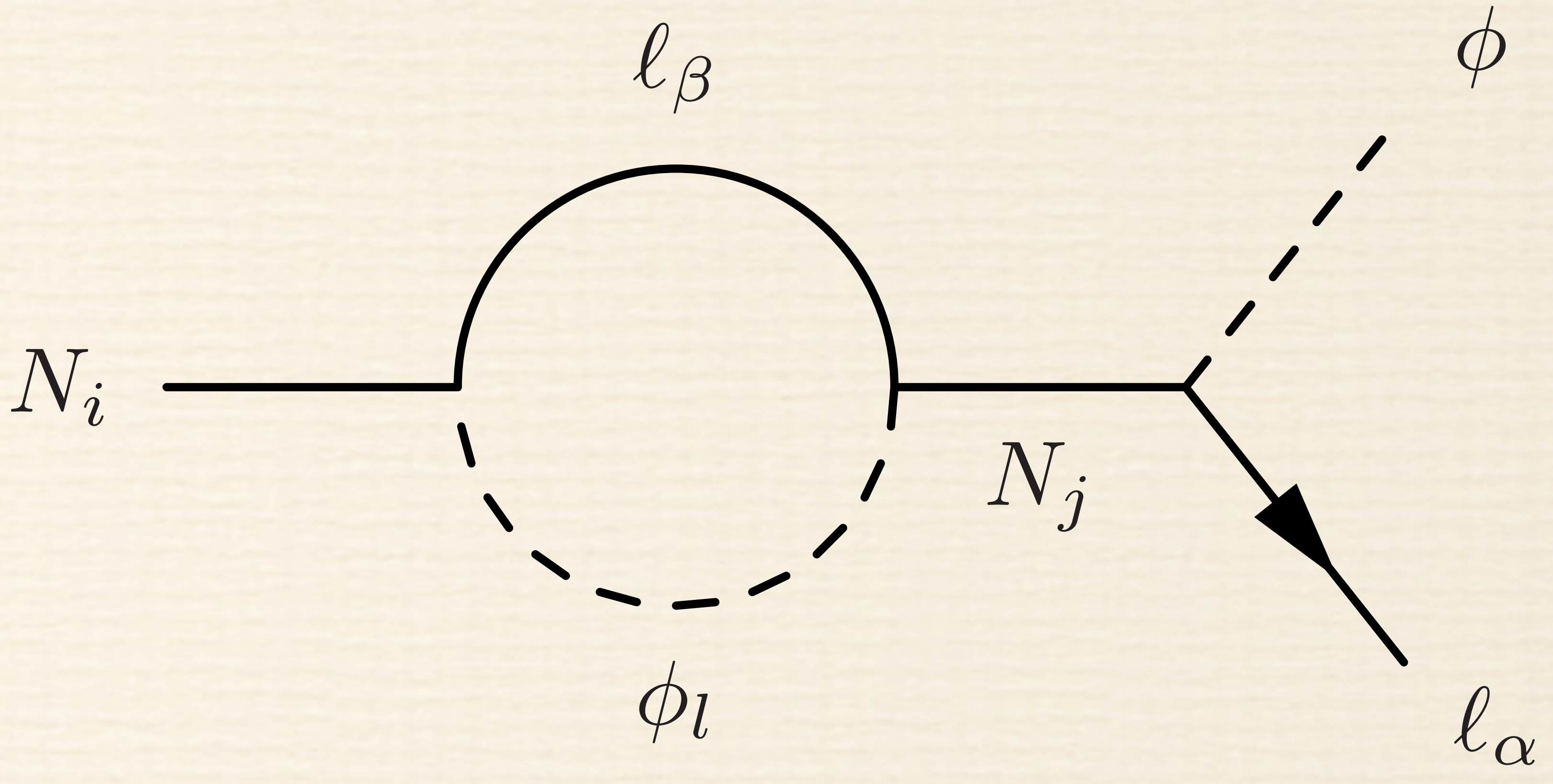
- Baryon asymmetry
- Decay of RH neutrinos: interference of tree and 1-loop diagrams



tree diagram



vertex diagram



wave-function diagram

- Lepton asymmetry can be transferred to quark asymmetry through EW sphaleron process
- Resonant leptogenesis: when N_i and N_j are quasi-degenerate in the wave-function diagram

Covi, Roulet, Vissani Phys.Lett.B 384 (1996) 169-174

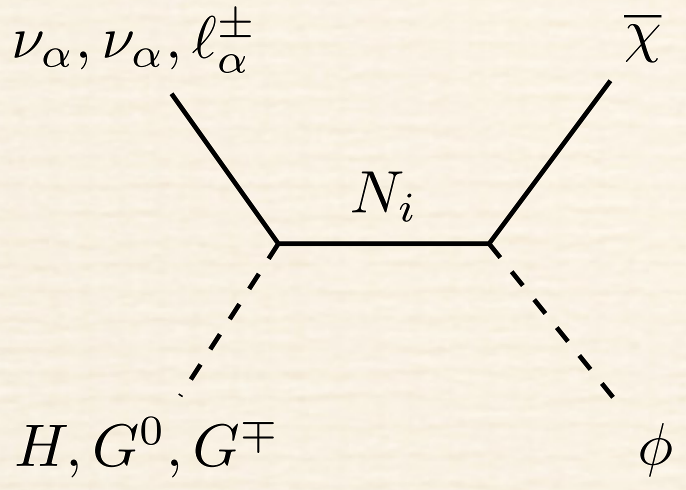
Neutrino Portal Dark Matter

- General neutrino portal: $y_i \phi \overline{\chi} N_i$ the dark particles are charged under a Z_2 symmetry

  dark scalar (ϕ) dark fermion ($\overline{\chi}$) RH neutrino (N_i)

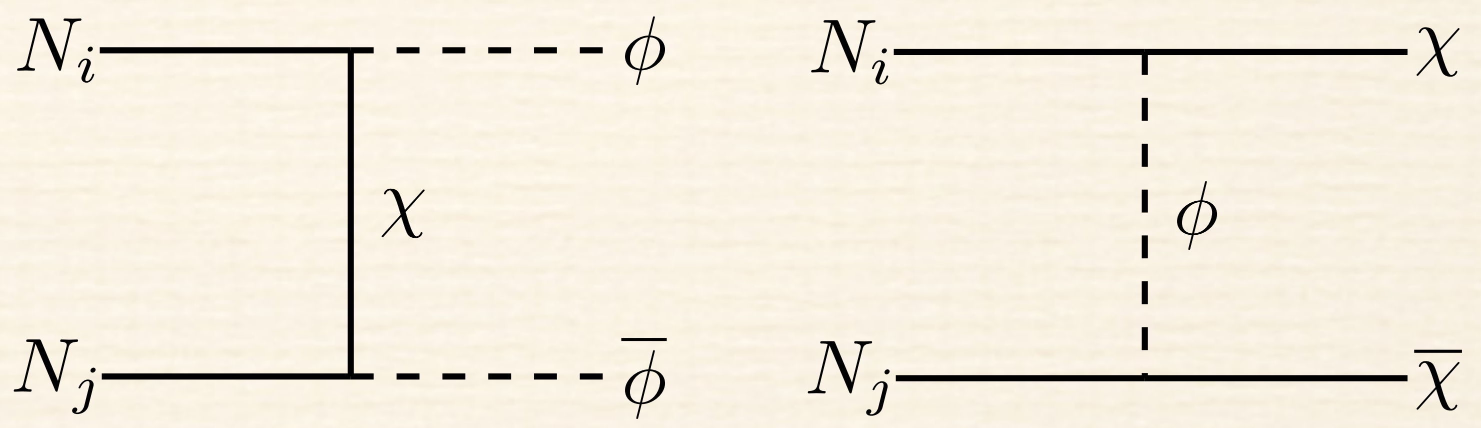
- heavy scalar scenario: $\phi \to \chi N_i$

- Freeze-in production of dark matter:



ν-Yukawa process $\propto Y^2 y^2$

↑ seesaw Yukawa



dark sector process $\propto y^4$

- ν-Yukawa dominance: sizeable Y

Chianese, Fu, King JCAP 03 (2020) 030

Neutrino Portal Dark Matter in the Littlest Seesaw model

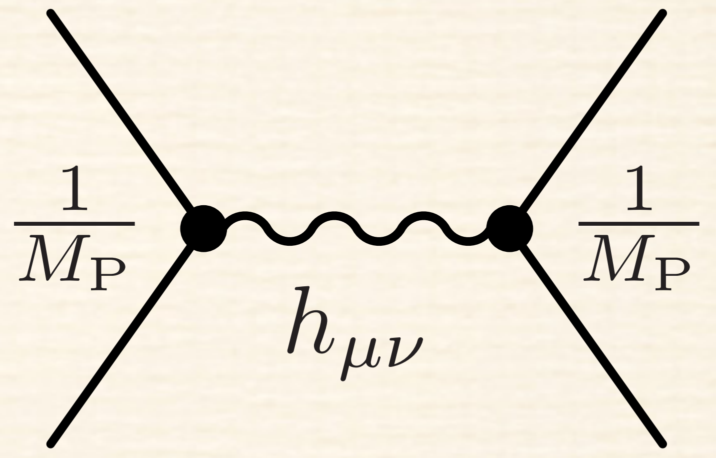
- ν-Yukawa interaction can dominate dark matter production when the RHN mass is above 4 TeV

Chianese, King JCAP 09 (2018) 027

- Leptogenesis in the Littlest Seesaw model: $M_{R1} = 5.1 \times 10^{10}$ GeV, $M_{R2} = 3.3 \times 10^{14}$ GeV

King, Sedgwick, Rowley JHEP 10 (2018) 184

- Production through graviton for superheavy particles



Chianese, Fu, King JCAP 06 (2020) 019

- Nevertheless, a ν-Yukawa dominant region can be found

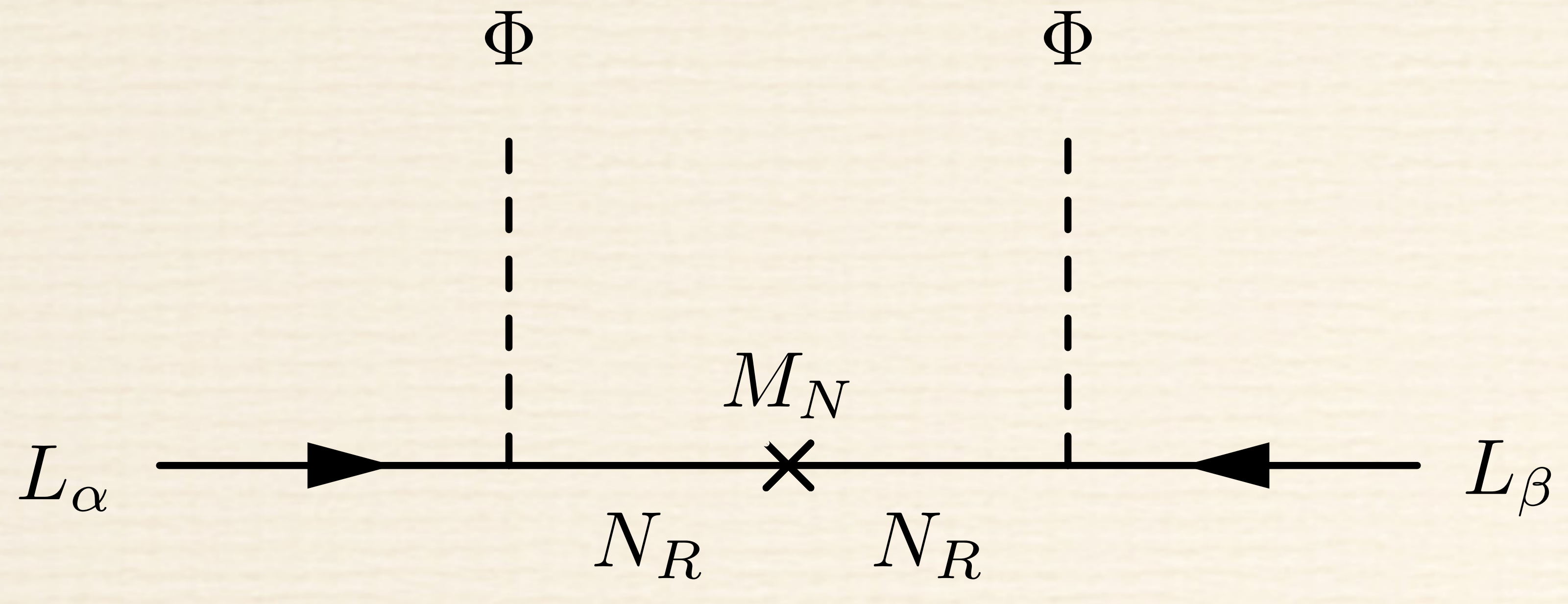
Chianese, Fu, King JCAP 01 (2021) 034

Predictive but not testable

**Q: Can we find a model where ν-Yukawa dominance can appear for GeV scale heavy neutrino?
And perhaps compatible with leptogenesis?**

Type Ib Seesaw Model

- Traditional type I seesaw mechanism (type Ia)

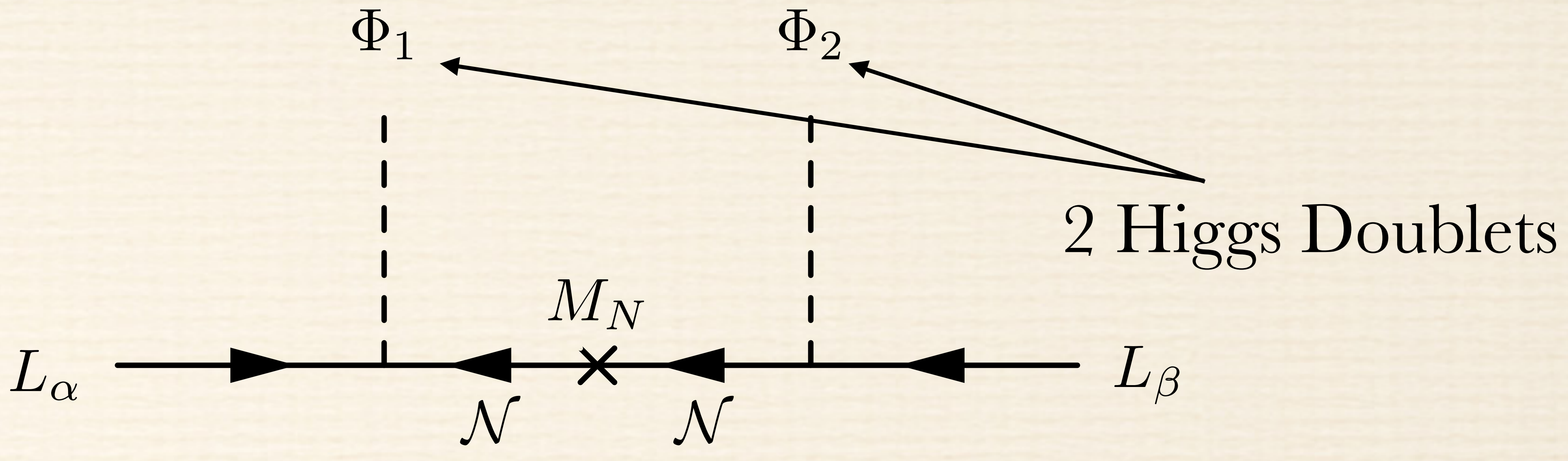


$$m \propto \frac{Y^2 v^2}{M_N}$$

- At least 2 Majorana RH neutrinos + 1 Higgs
- 1 Yukawa coupling for each RH neutrino
- 2 free parameters after considering neutrino mass an mixing: M_{R1} and M_{R2}
- To have a sizeable coupling, the right-handed neutrino has to be above TeV scale

- Type Ib seesaw mechanism

Hernandez-Garcia, King JHEP 05 (2019) 169



$$m \propto \frac{Y_1 Y_2 v_1 v_2}{M_N}$$

- 1 Dirac neutrino +2 Higgs
- 1 Yukawa coupling for each Higgs
- 3 free parameters after considering neutrino mass an mixing: Y_1, Y_2 and M_N
- One of Y_1, Y_2 can be small while the other one is sizeable, providing GeV scale heavy neutrino

Type Ib Seesaw Model in Cosmology

- Since one of the seesaw couplings can be large for GeV scale heavy neutrino in the type Ib seesaw mode, the dark matter and neutrino physics can be connected through neutrino portal at GeV scale, which can be further constrained by multiple collider experiments Chianese, Fu, King JHEP 05 (2021) 129
- In an extended model with a superheavy third RHN and a scalar field, the type Ib seesaw mechanism can be realised effectively at low energy effectively with a pseudo-Dirac heavy neutrino and baryon asymmetry can be explained by resonant leptogenesis in the parameter space where neutrino physics can be connected to dark matter problem Fu, King Phys.Rev.D 105 (2022) 9, 095001
- As the neutrino is Dirac in the type Ib seesaw model, it can be charged under a U(1)' gauge symmetry which breaks into a Z_2 symmetry that stabilises a Majorana dark matter candidate spontaneously Fu, King JHEP 12 (2021) 121

Summary

- Indication of BSM physics: neutrino mass and mixing, dark matter, baryon asymmetry
- Neutrino physics can be related to dark matter through a neutrino portal, but the connection is not testable
- A new type Ib seesaw model can make a testable connection between neutrino physics and dark matter which can also explain baryon asymmetry through leptogenesis

Thank You!