Neutrino Mass and the Early Universe

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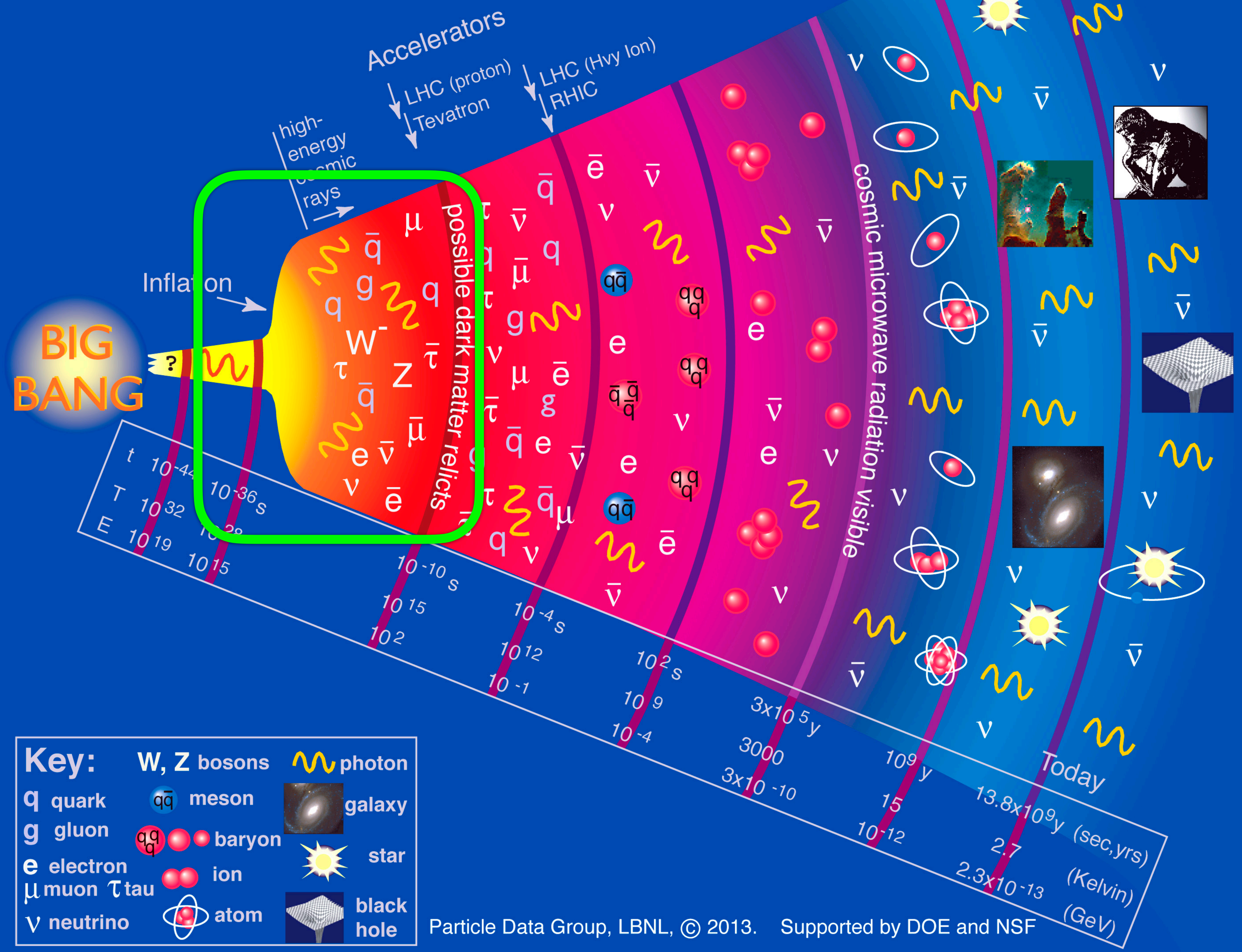
In collaboration with Marco Chianese

International School of Nuclear Physics : 43rd Course
Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics

History of the Universe



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Outline

- Cosmology problems
- Neutrino portal dark matter: limitation of type I seesaw model
- New model: Type Ib seesaw model in cosmology

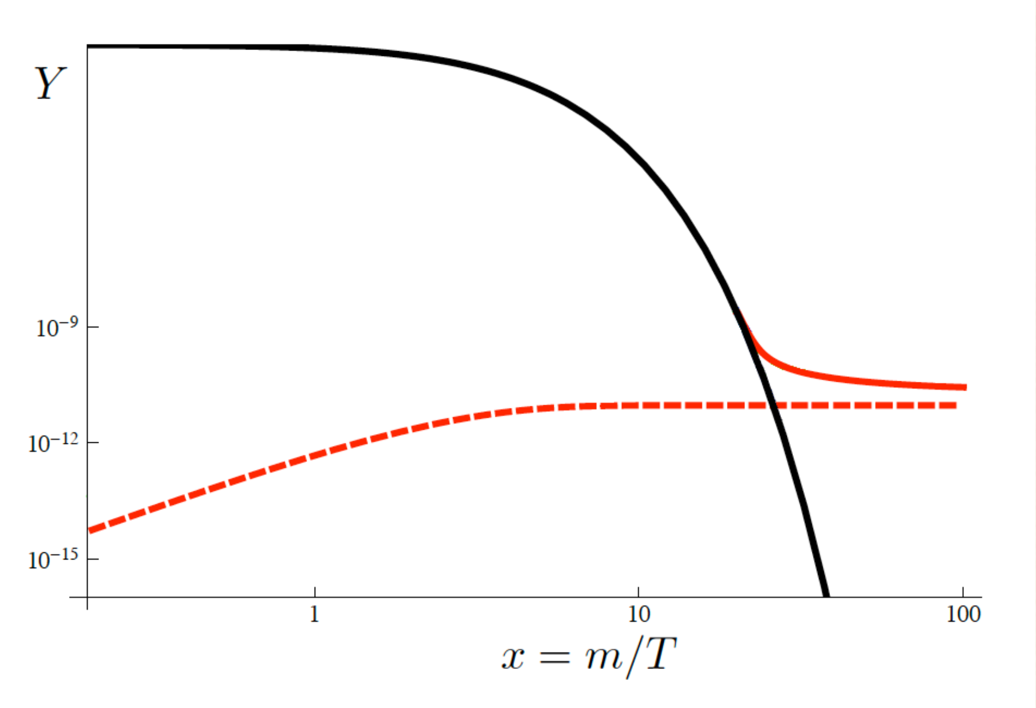
Dark Matter Production

- Boltzmann equation

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

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

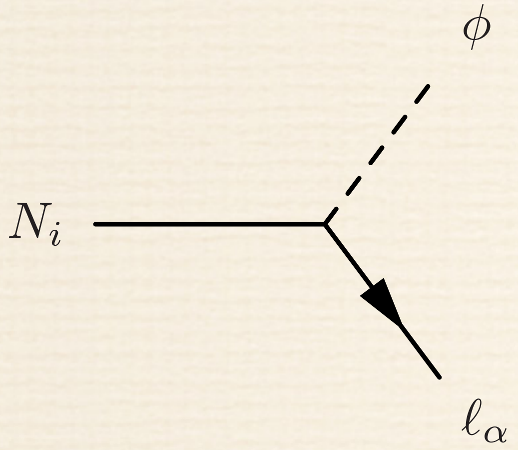
- Freeze-out: The particle is in equilibrium with the thermal bath after reheating. As the universe cools down, the particle decouples from the thermal bath.
- Freeze-in: The particle is out of equilibrium after reheating (usually with negligible initial abundance). The particle is produced gradually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



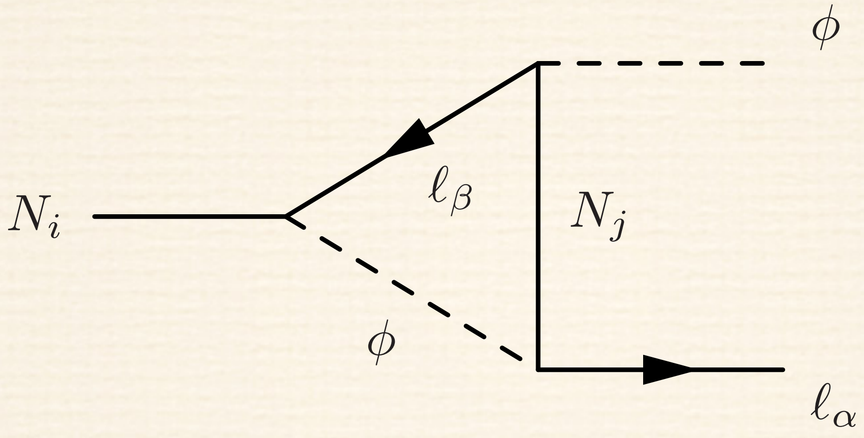
- The observed DM relic abundance gives a constraint $\Omega_{\rm DM}^{\rm obs} h^2 = 0.120 \pm 0.001$ 1807.06209

Leptogenesis

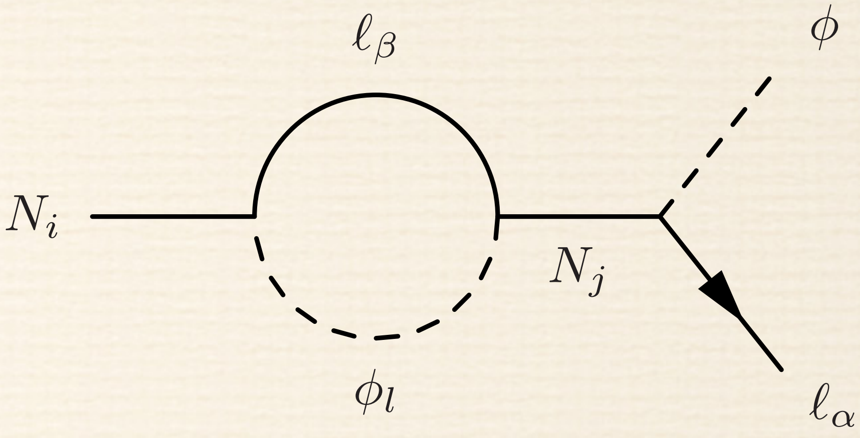
- Baryon asymmetry
- Solution to baryon asymmetry from neutrinos
- Decay of RH neutrinos: interference of tree and 1-loop diagrams



tree diagram



vertex diagram



wave-function diagram

- Lepton asymmetry can be transferred to quark asymmetry through EW sphaleron process

Phys.Lett.B 384 (1996) 169-174

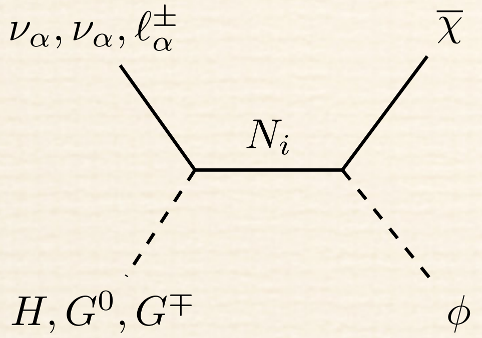
- Resonant leptogenesis: when N_i and N_j are quasi-degenerate in the wave-function diagram

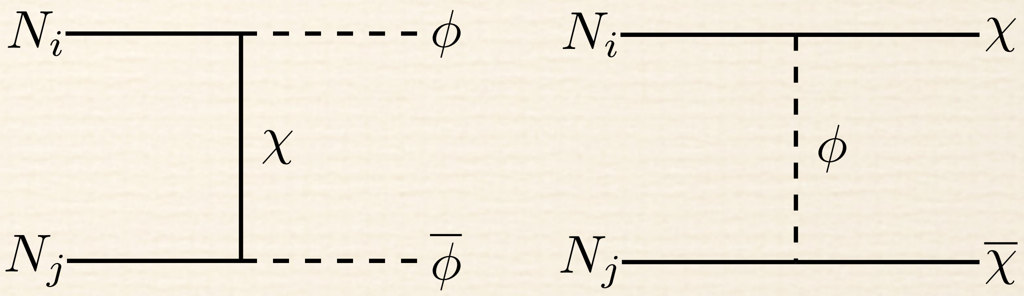
Neutrino Portal Dark Matter

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

dark scalar dark fermion RH neutrino

- 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

JCAP 03 (2020) 030

Neutrino Portal Dark Matter in the Littlest Seesaw model

- The Littlest Seesaw model: a version of type I seesaw model explaining neutrino mass and mixing with two RH neutrinos and minimal free parameters

JHEP 02 (2016), 085

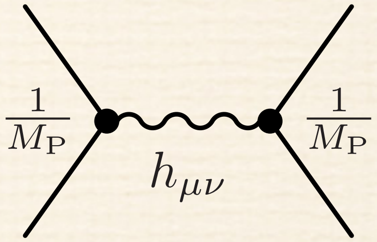
- ν-Yukawa interaction can only dominate dark matter production when the RHN mass is above 4 TeV

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

JHEP 10 (2018) 184

- Production through graviton for superheavy particles



JCAP 06 (2020) 019

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

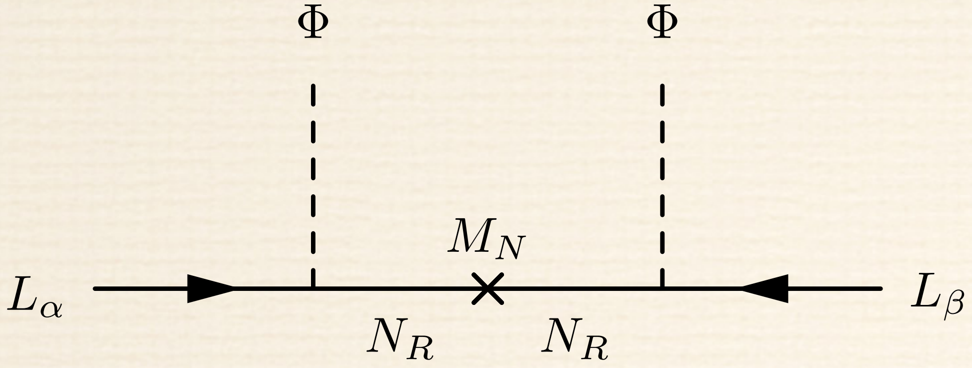
JCAP 01 (2021) 034

Predictive but not testable for collider experiments

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

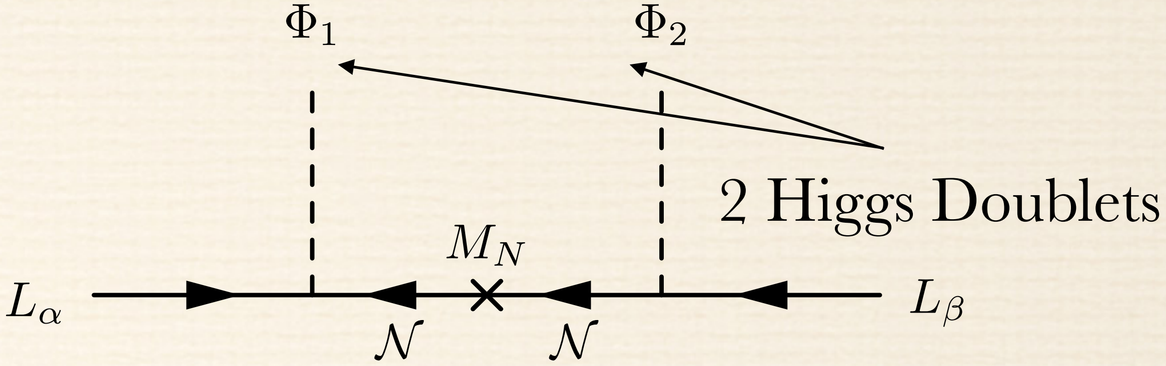
- Traditional type I seesaw mechanism (Littlest Seesaw)



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

- 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



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

- 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

JHEP 05 (2019) 169

Type Ib Seesaw Model with a Neutrino Portal

- Particles and symmetries

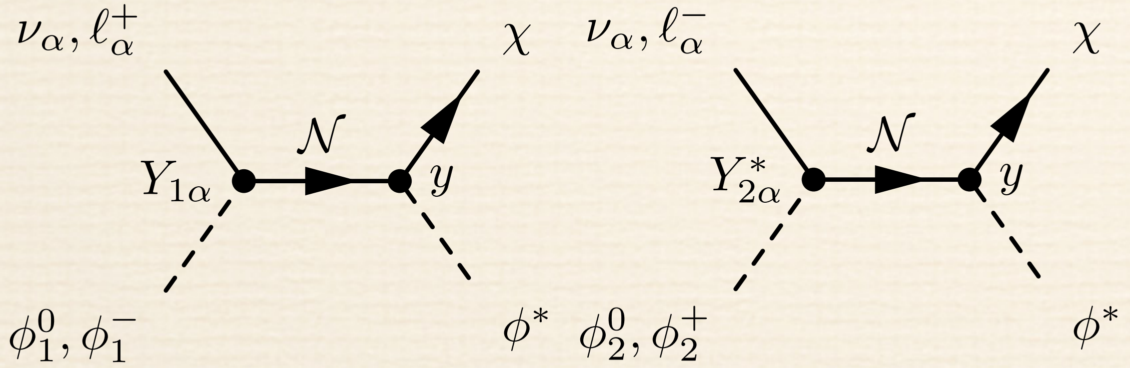
	Q_α	$u_{R\beta}$	$d_{R\beta}$	L_α	$e_{R\beta}$	Φ_1	Φ_2	N_{R1}	N_{R2}	ϕ	$\chi_{L,R}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	$-\frac{1}{2}$	0	0	0	0
Z_3	1	ω	ω	1	ω	ω	ω^2	ω^2	ω	ω	ω^2
Z_2	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$-$	$-$

- Seesaw Lagrangian and neutrino portal $\mathcal{N} = (N_{R1}^c, N_{R2})$

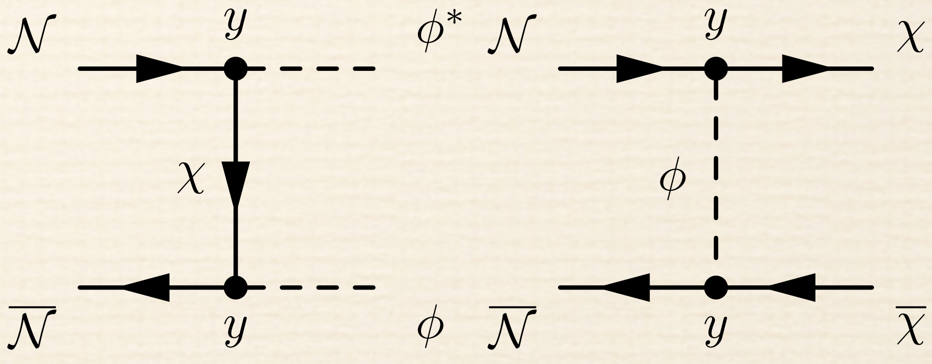
$$\mathcal{L}_{\text{seesawIb}} = -Y_{1\alpha}^* \overline{L^c}_\alpha \Phi_1^* \mathcal{N}_L - Y_{2\alpha} \overline{L}_\alpha \Phi_2 \mathcal{N}_R - M_N \overline{\mathcal{N}_L} \mathcal{N}_R + \text{h.c.}$$

$$\mathcal{L}_{\mathrm{N_R portal}} = y\phi\,\overline{\chi}\mathcal{N} + \text{h.c.}$$

- Freeze-in production of dark matter



Neutrino-Yukawa processes



Dark sector processes

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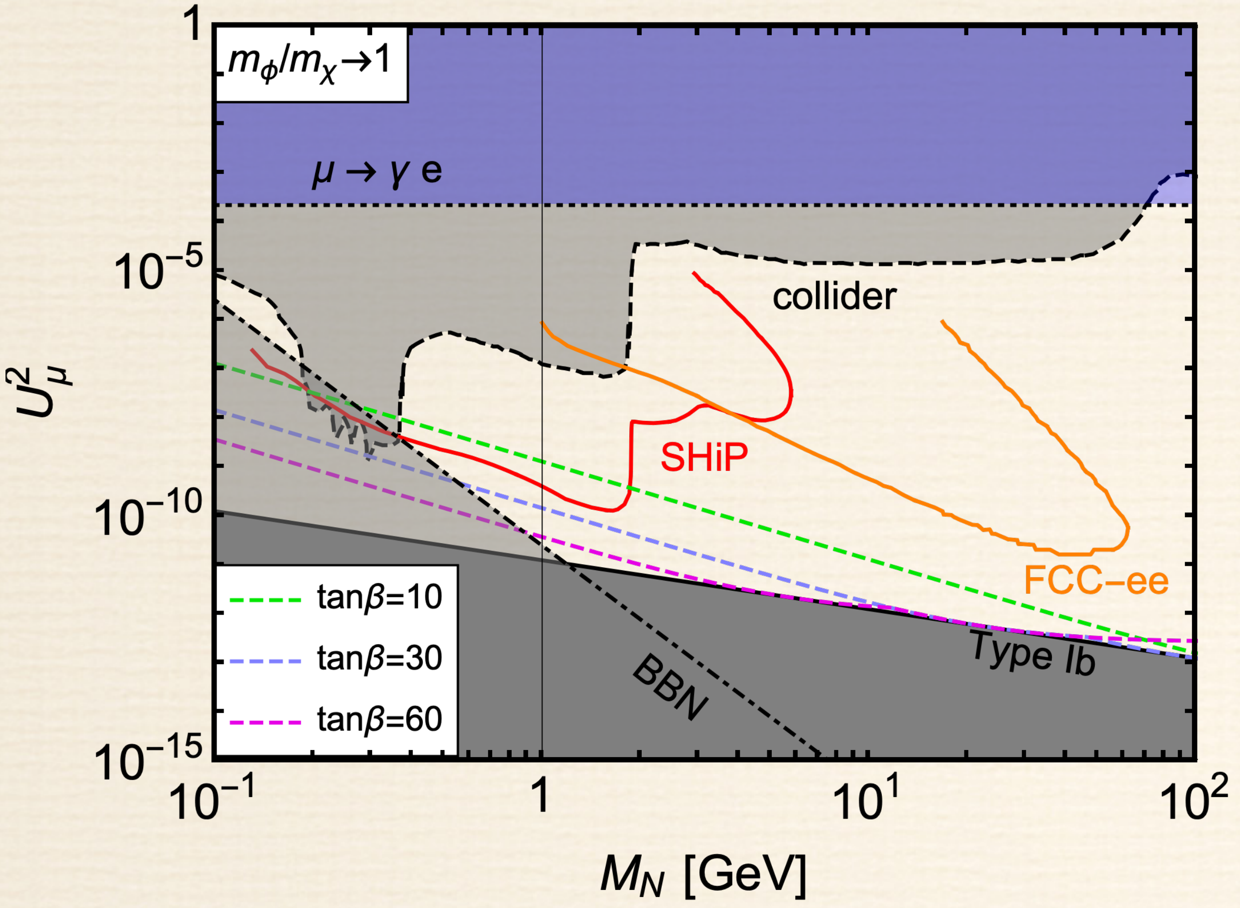
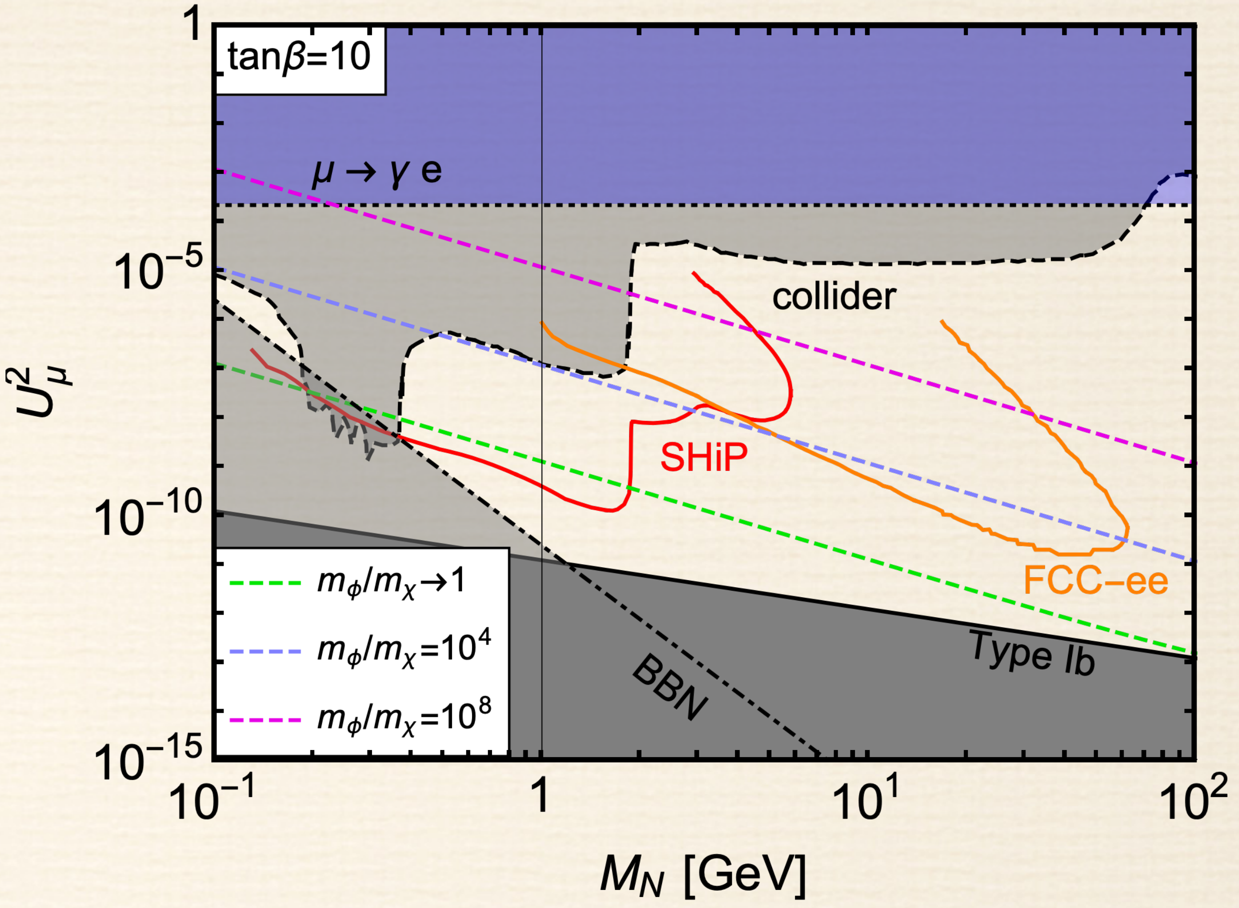
Relation to Experiments





- 2 key parameters:
  - tanβ: the ratio of VEVs of the Higgs v_2/v_1
  - m_ϕ/m_χ: For hierarchical mass spectrum, the dark matter production depends on m_ϕ/m_χ
- U^2: active-sterile neutrino mixing strength

- The strongest constraint is given by ν_μ mixing
- ν-Yukawa dominance is allowed above the coloured dashed lines
- Less constrained as tanβ increases
- More constrained as m_ϕ/m_χ increases

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Resonant Leptogenesis in Type Ib Seesaw Model

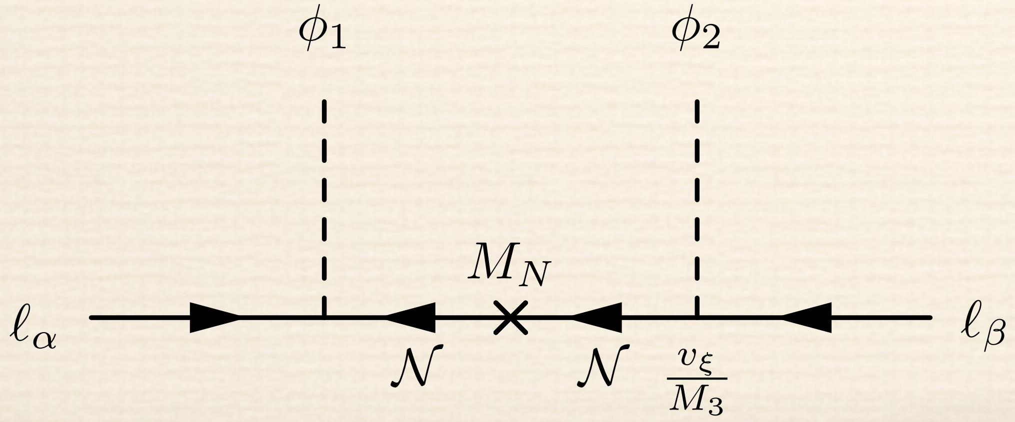
- An extended model with a superheavy third RHN and a scalar field

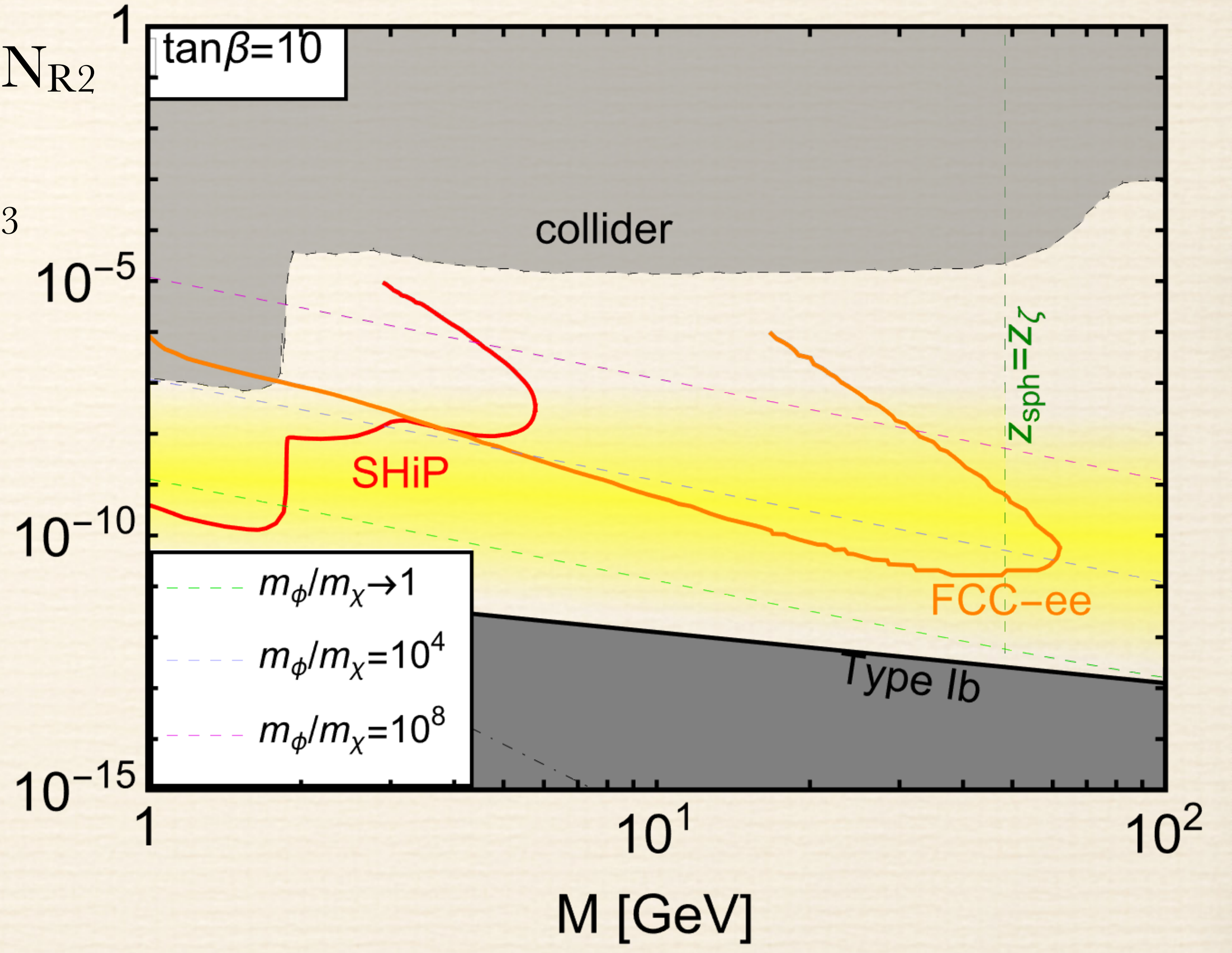
$$\mathcal{L}_{\text{seesawIb}} = -Y_{1\alpha}\bar{\ell}_\alpha\phi_1 N_{R1} - Y_{3\alpha}\bar{\ell}_\alpha\phi_2 N_{R3} - 2Y_{13}\bar{\xi}\,\overline{N^c_{R3}}N_{R1} - 2Y_{23}\xi\overline{N^c_{R3}}N_{R2} \\ - M\overline{N^c_{R1}}N_{R2} - \frac{1}{2}M_3\overline{N^c_{R3}}N_{R3} + \text{h.c.}$$

- After the scalar field gains a VEV, N_{R1} and N_{R2} gain mass splitting through mixing with N_{R3}

$$\Delta M_{12} = \frac{\Re\left[(M_{13} - M_{23})^2\right]}{2M_{33}}$$

- Type Ib seesaw mechanism can be realised effectively at low scale





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Summary

- Indications of BSM physics: neutrino mass and mixing, dark matter, baryon asymmetry
- Neutrino physics can be related to dark matter through a neutrino portal in type I seesaw model, 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!