Institute for Cosmic Ray Research
University of Tokyo

Cosmology and Particle Phenomenology

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Elementary Particle Physics and Cosmology

Ultimate Goal

Complete theory: to understand
i) The elemental constituents of matter and their interactions
ii) How the Universe begun and has evolved

Complete Theory

String Theory | Supersymmetry | Grand Unification

It seems still very difficult to reach the complete theory…

The Standard Model and Beyond

Our current foundation: The SM is successful, but “effective” theory.

Complete Theory

String Theory | Supersymmetry | Grand Unification

↑

Extension of the SM

↑

Phenomena beyond the SM and anomalies

- Neutrino oscillation
- Muon g-2
- B anomalies
- …
- Dark Matter
- Baryon Asymmetry of the Universe
- Inflation
- …

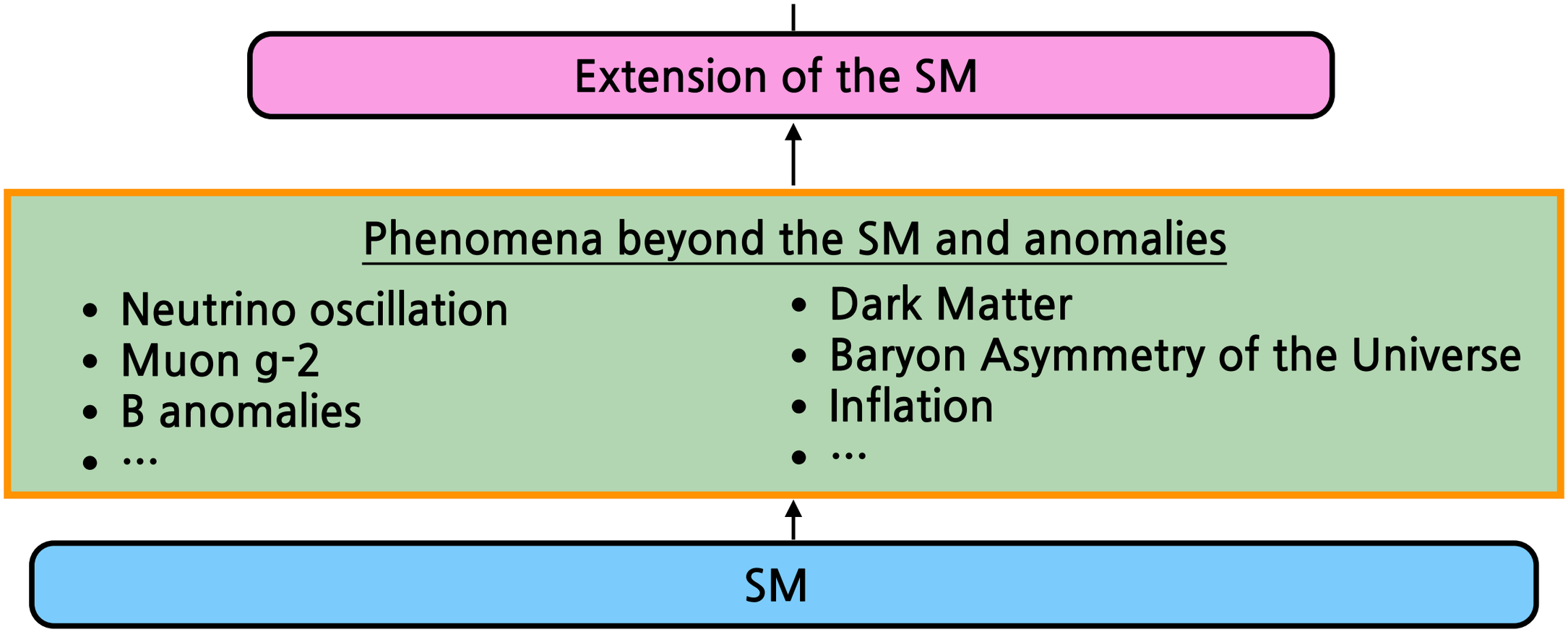
↑

SM

What theorists are doing

To consider feasible extensions of the SM and their verifiability

- build new model [adding new symmetry/particle/interaction]
- explain phenomena beyond the SM/anomalies
- derive predictions in the new model



ICRR Theory Group

Particle Cosmology and Phenomenology

Theory group studies a variety of topic.

Cosmology
by Prof. M.Kawasaki

Phenomenology
by Assoc.Prof. M.Ibe

Primordial Black Hole

Dark Matter

Inflation

Axions

Baryon Asymmetry of the Universe

Big-Bang Nucleosynthesis

Beyond the SM

Recent publications

We tackle each problem with various approaches.

Cosmology
by Prof. M.Kawasaki

Phenomenology
by Assoc.Prof. M.Ibe

Primordial Black Holes

"Gravitational waves from type II axion-like curvaton model and its implication for NANOGrav result" (Nakatsuka)

Dark Matter

"Cosmological Constraint on Vector Mediator of Neutrino-Electron Interaction in light of XENON1T Excess" (Kobayashi, Nakayama)

"Probing dark matter self-interaction with ultrafaint dwarf galaxies" (Kobayashi, Nakayama)

"Ultralight vector dark matter search with auxiliary length channels of gravitational wave detectors" (Nakatsuka)

Inflation

"Statistically-Anisotropic Tensor Bispectrum from Inflation" (Murai)

"Detection of isotropic cosmic birefringence and its implications for axionlike particles including dark energy" (Murai, Nakatsuka)

Axions

"Probing Oscillons of Ultra-Light Axion-like Particle by 21cm Forest" (Nakatsuka)

"On Stability of Fermionic Superconducting Current in Cosmic String" (Kobayashi, Nakayama)

Baryon Asymmetry of the Universe

"Affleck-Dine inflation in supergravity"

Big-Bang Nucleosynthesis

"Big Bang Nucleosynthesis constraints on sterile neutrino and lepton asymmetry of the Universe" (Murai)

"Big Bang Nucleosynthesis with sub-GeV massive decaying particles" (Murai)

Beyond the SM

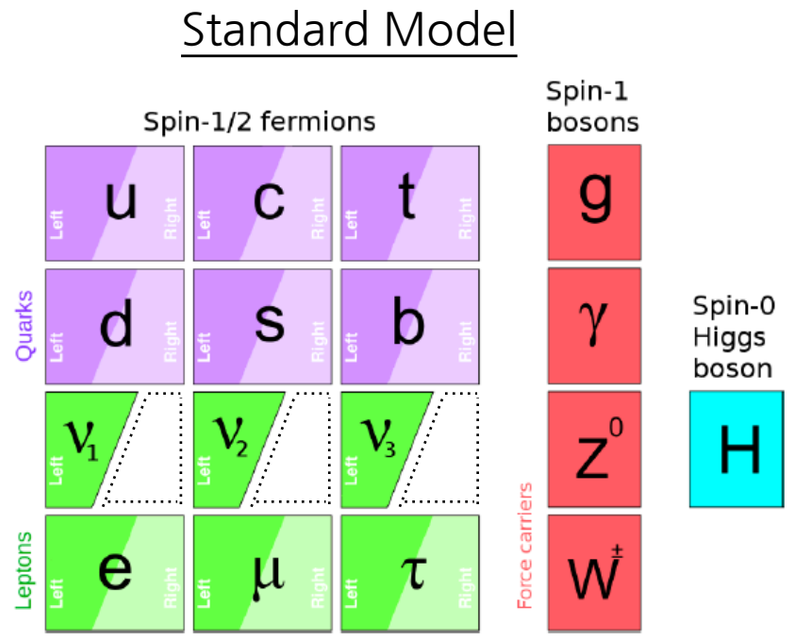
"Proton Decay in Product Group Unification"

My Research

Extension with Right-handed Neutrinos

Neutrino is the most mysterious particle in the SM.

- Mass: Absolute values and Hierarchy
- Nature: Dirac or Majorana
- Feature: CP and unitary violation



Origin of neutrino mass

See-saw mechanism

$$\nu_R$$

Dark matter

Sterile neutrino

Baryon asymmetry of the Universe

Leptogensis

See-saw Mechanism

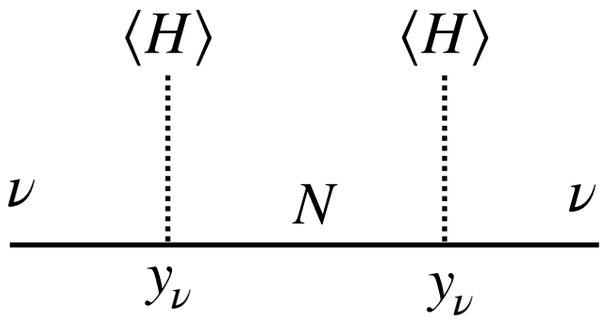
[Minkowski ('77)] [Yanagida ('79)] [Gell-Mann, Ramond, Slansky ('79)] [Glashow ('79)] [Mohapatra, Senjanovic ('79)]

Yukawa interaction of neutrinos generates the tiny mass.

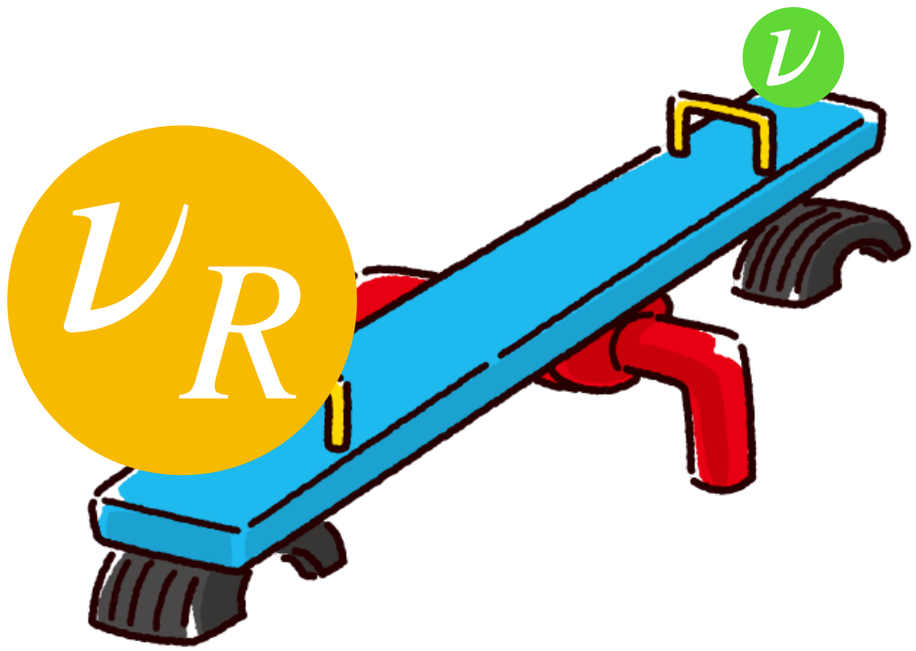
Dirac mass: $y\langle H\rangle\bar{\Psi}_L\Psi_R \equiv m_D\bar{\Psi}_L\Psi_R$

For neutrinos, $y_\nu \approx 10^{-12} \ll y_e$ ⟶ Unnatural

Majorana mass: $m_\nu\,\bar{\nu}\,\nu^c$



$$m_\nu \sim \frac{y_\nu^2\langle H\rangle^2}{M_R}$$

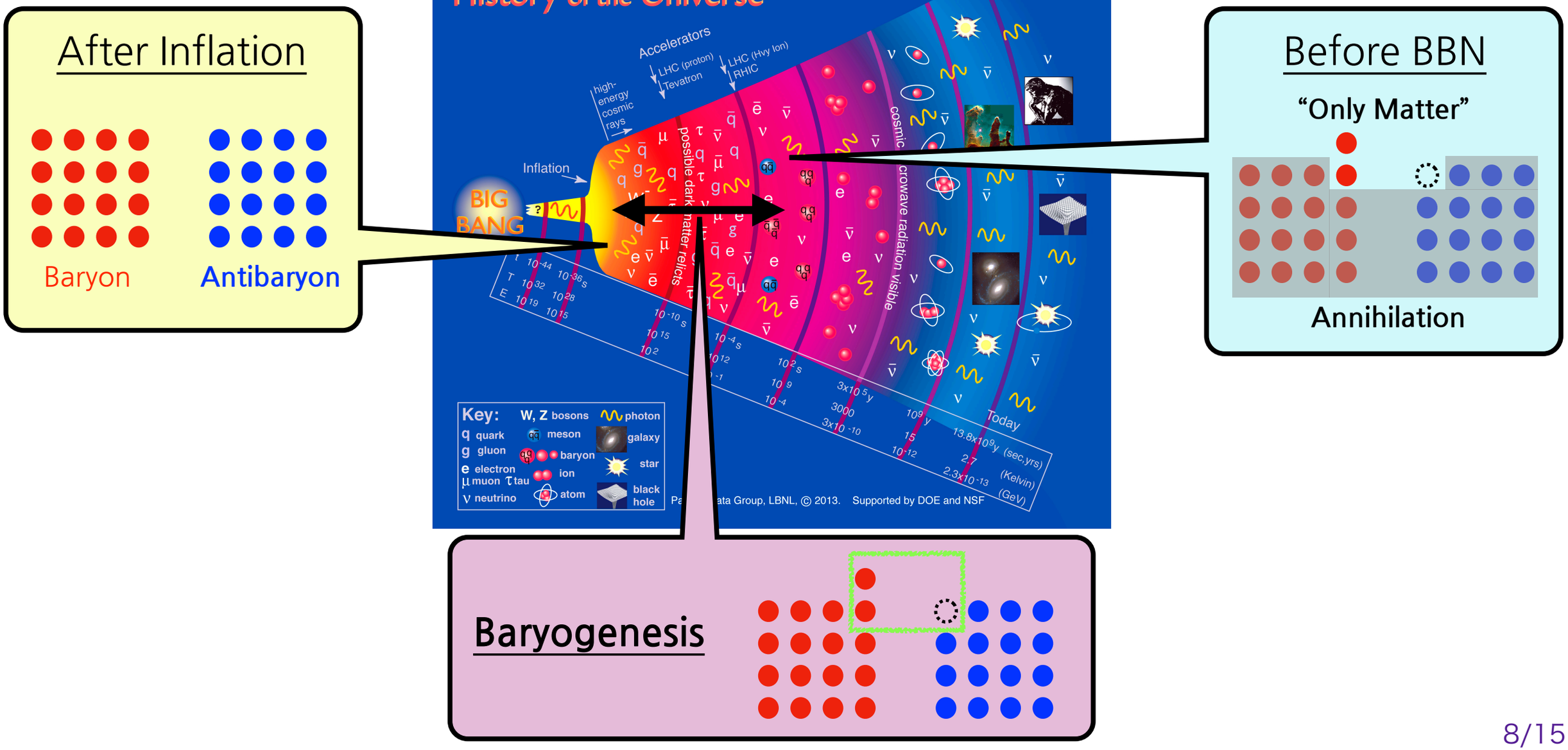


⟶
- Active neutrinos w/ m_ν for neutrino oscillations
- Heavy neutrinos ($\sim \nu_R$) w/ M_R for Baryogenesis

Baryon asymmetry of the Universe

Our matter-dominated universe must be realized.

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10}$$



Leptogenesis

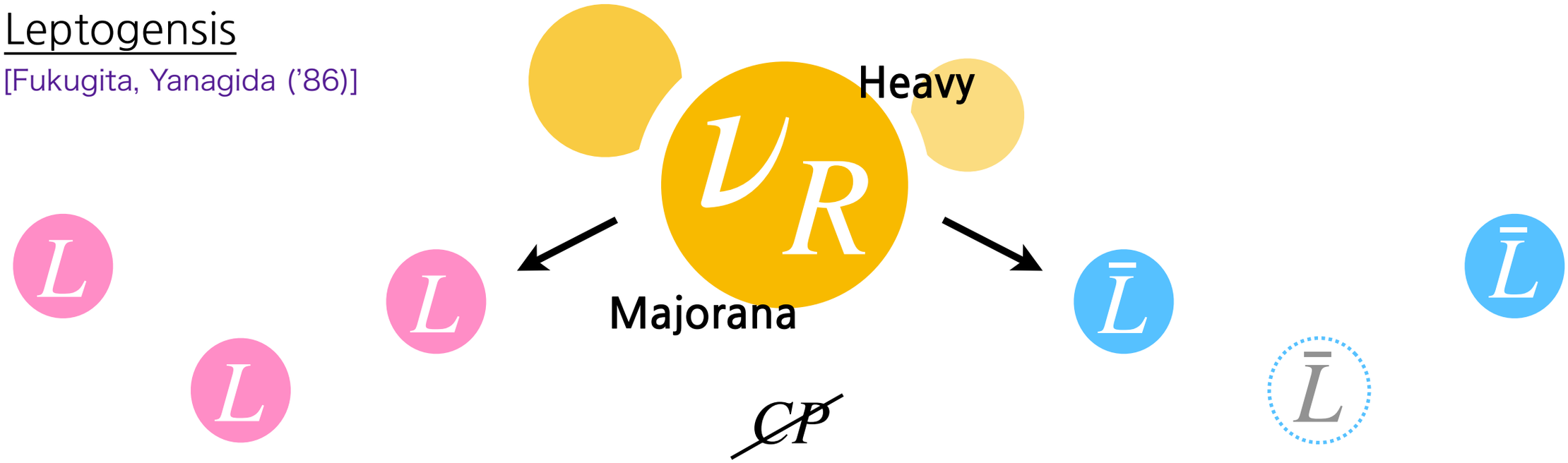
ν_R can generate the matter-antimatter asymmetry in the primordial Universe.

Sakharov conditions [Sakharov ('67)]

1. B violation
2. C and CP violation ⟶ Particle-antiparticle asymmetry
3. Deviation from equilibrium ⟶ Irreversible process

Leptogensis

[Fukugita, Yanagida ('86)]

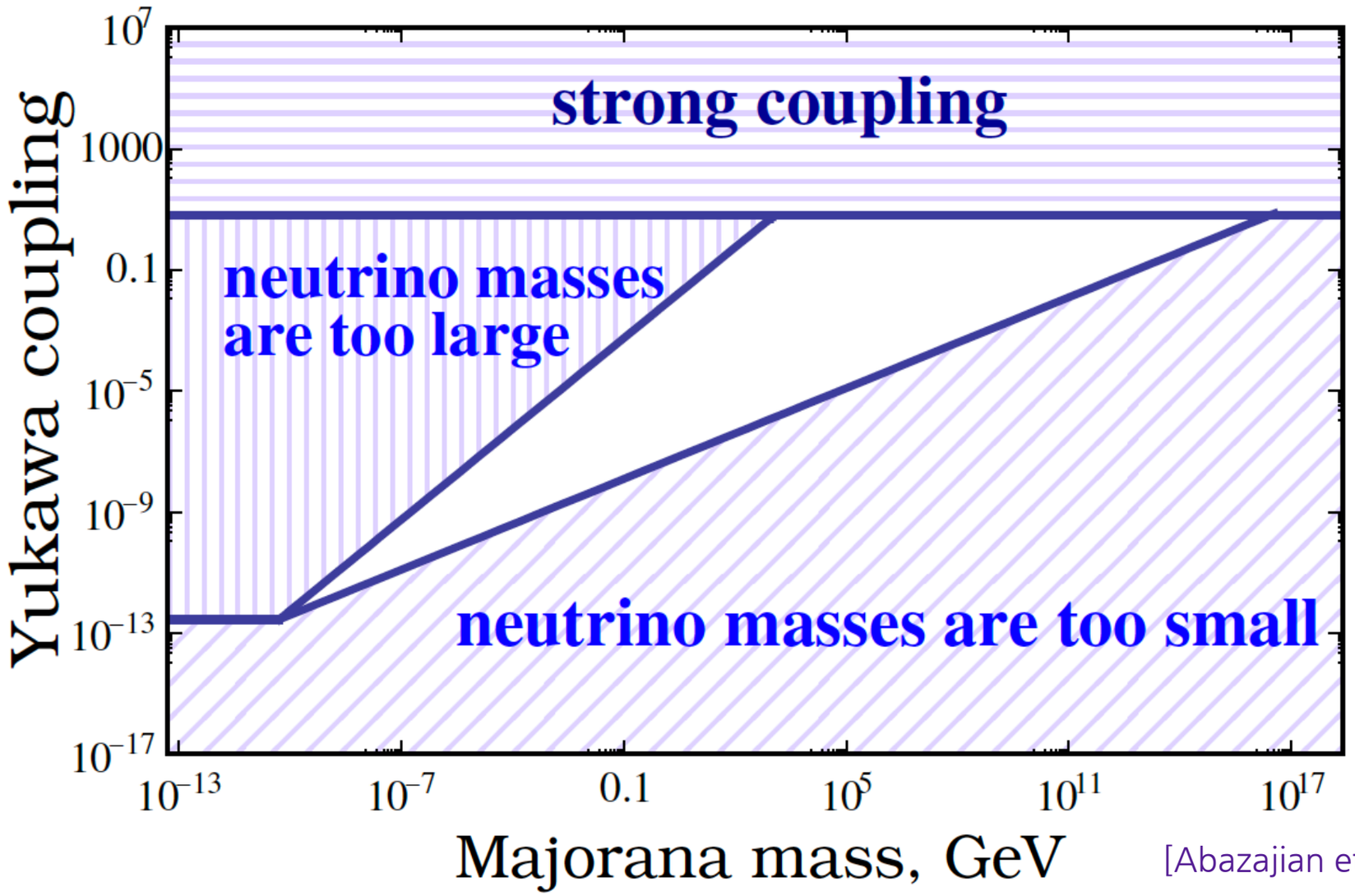


$$n_L - n_{\bar{L}} \neq 0 \longrightarrow n_B - n_{\bar{B}} \neq 0$$

$L \to B$ conversion by Sphaleron

What We Know about ν_R from See-saw

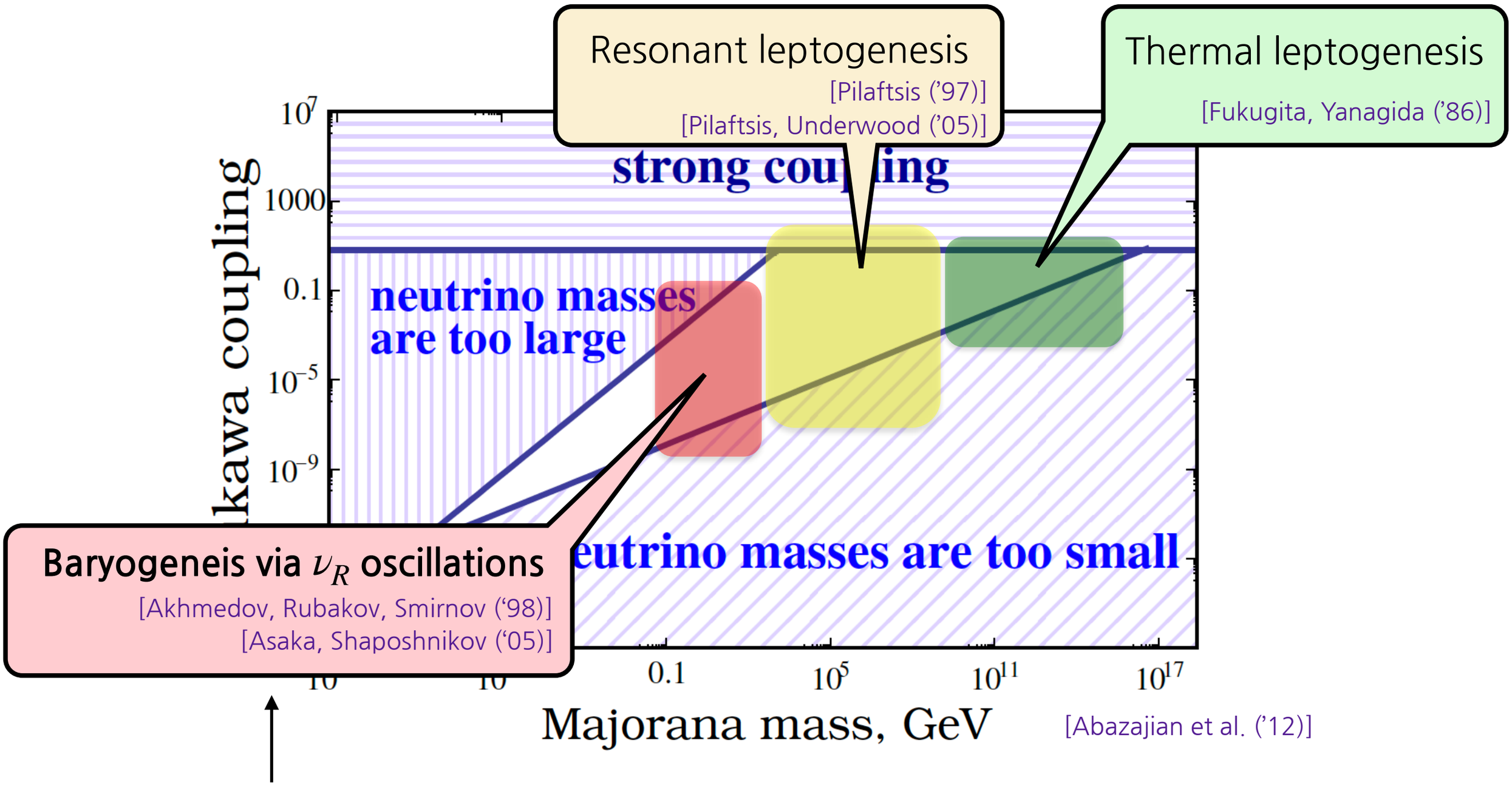
In the wide region of parameter space neutrino oscillations can be explained.



[Abazajian et al. ('12)]

What We Know about ν_R from Leptogenesis

Leptogenesis can work for each mass scale.



[Abazajian et al. ('12)]

Interesting in terms of testability!

Leptogensis via Right-handed Neutrino Oscillations

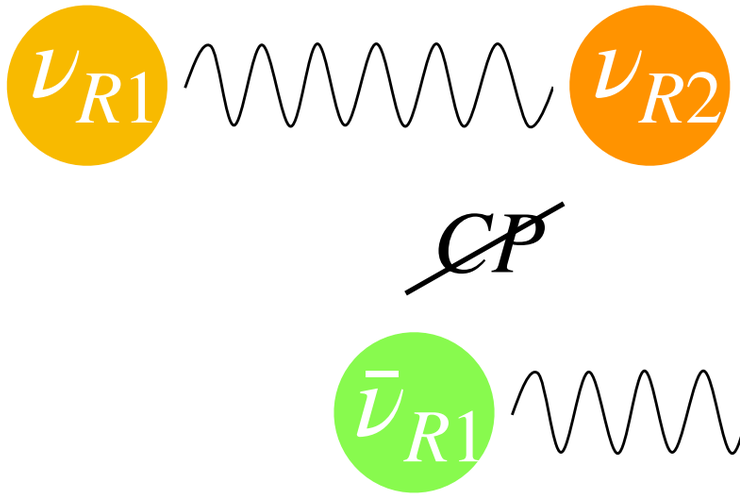
Parameter space for successful baryogenesis is a motivated target to explore.

$y_\nu \ll 1$ ⟶ Decoupled from thermal plasma

Relativistic ⟶ Oscillation of ν_R

$$U_{\alpha I} \equiv \frac{\langle H \rangle}{M_R}[y_\nu]_{\alpha I}$$

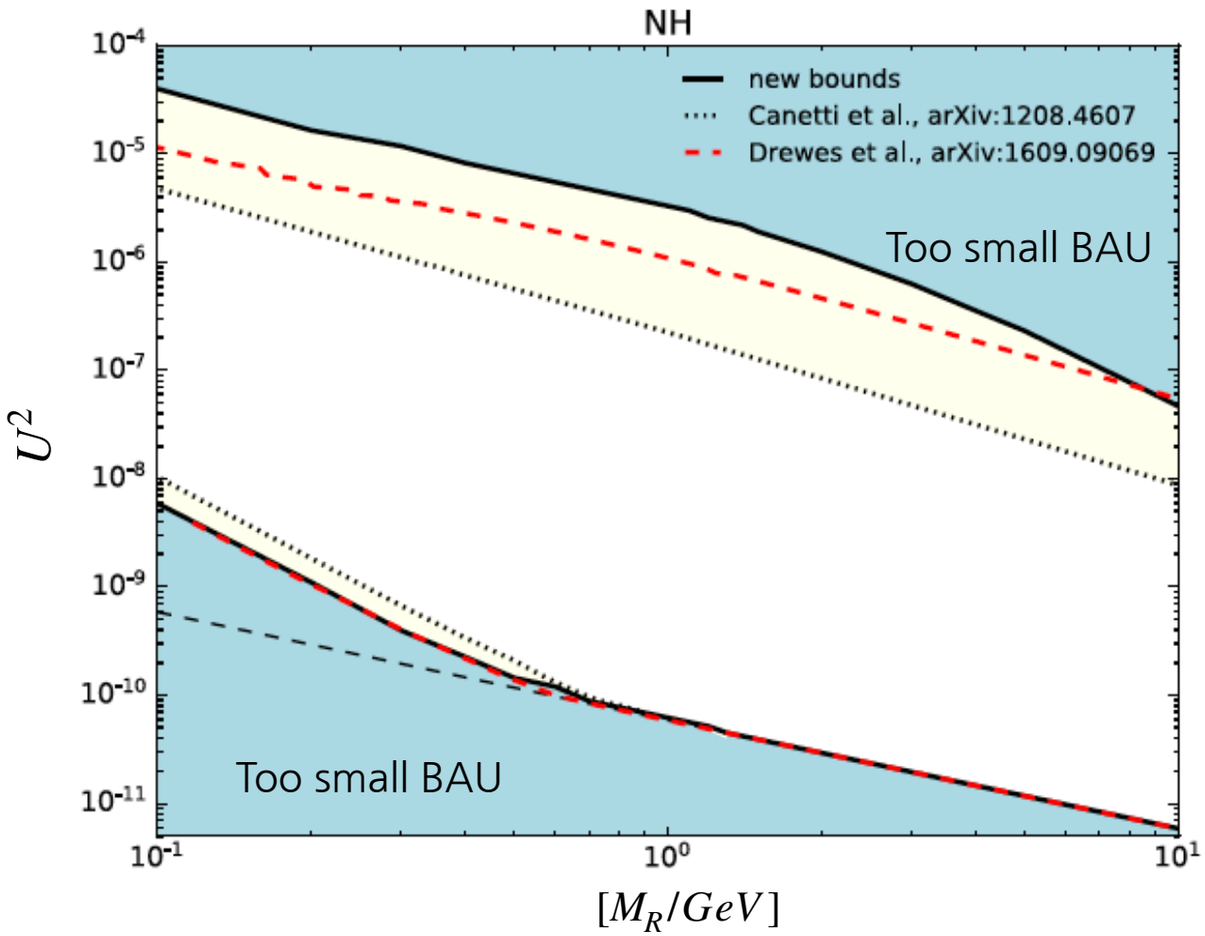
$U^2 \equiv \sum_{\alpha,I} |U_{\alpha I}|^2$: Typical mixing between $\nu_{L\alpha}$ and ν_{RI}



$$n_R - n_{\bar{R}} \neq 0$$

$$n_L - n_{\bar{L}} \neq 0 \longrightarrow n_B - n_{\bar{B}} \neq 0$$

$L \to B$ conversion (Sphaleron)



[SE, Shaposhnikov, Timiryasov ('18)]

How to Search for Heavy Neutrinos

Heavy neutrinos couple to leptons and mesons with weak interaction and active-sterile mixing, $U_{\alpha I} \ll 1$.

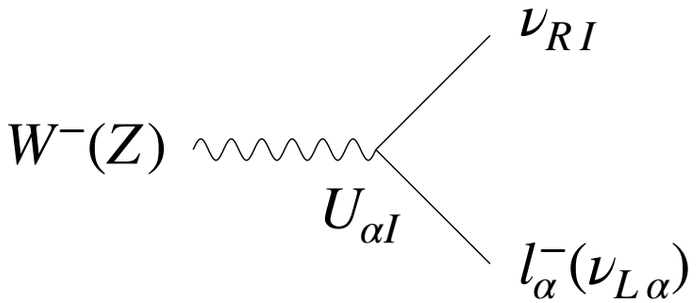
Super Kamiokande

ν_R produced in atmosphere

[Asaka, Watanabe ('12)]

Peak search

In charged lepton spectrum from stoped π, K decays



Production

$$M^- \longrightarrow \nu_{R\,I} + l_\alpha^-$$

$$\alpha = e, \mu, \tau$$

Decay

$$\nu_{R\,I} \longrightarrow l_\alpha^- + l_\beta^+ + \nu_\beta$$
$$\longrightarrow M^+ + l_\alpha^-$$

$$M = \pi, K, \ldots, B$$

Displaced vertex in detectors of colliders

Search for long-lived particles heavier than B

Displaced detectors in collider Exps.

FASER, MATHUSLA, ANNUBIS, etc.

T2K near detector

Decays of ν_R produced K, the source of ν beam

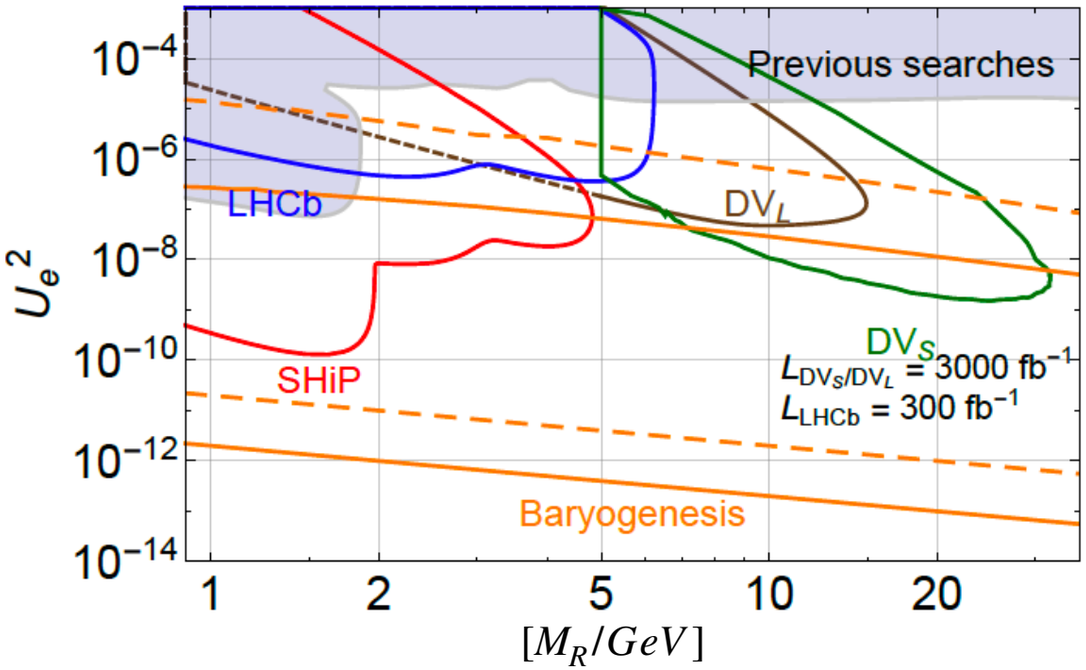
[Asaka, SE, Watanabe ('13)] [T2K collaboration ('19)]

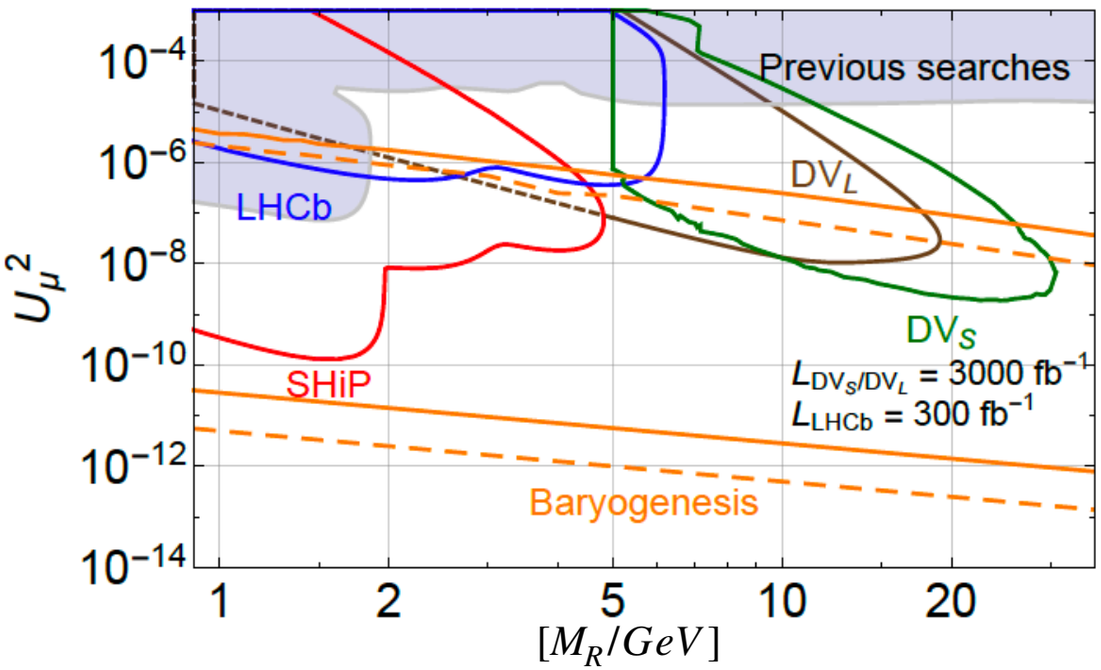
Beam-dump Exps.

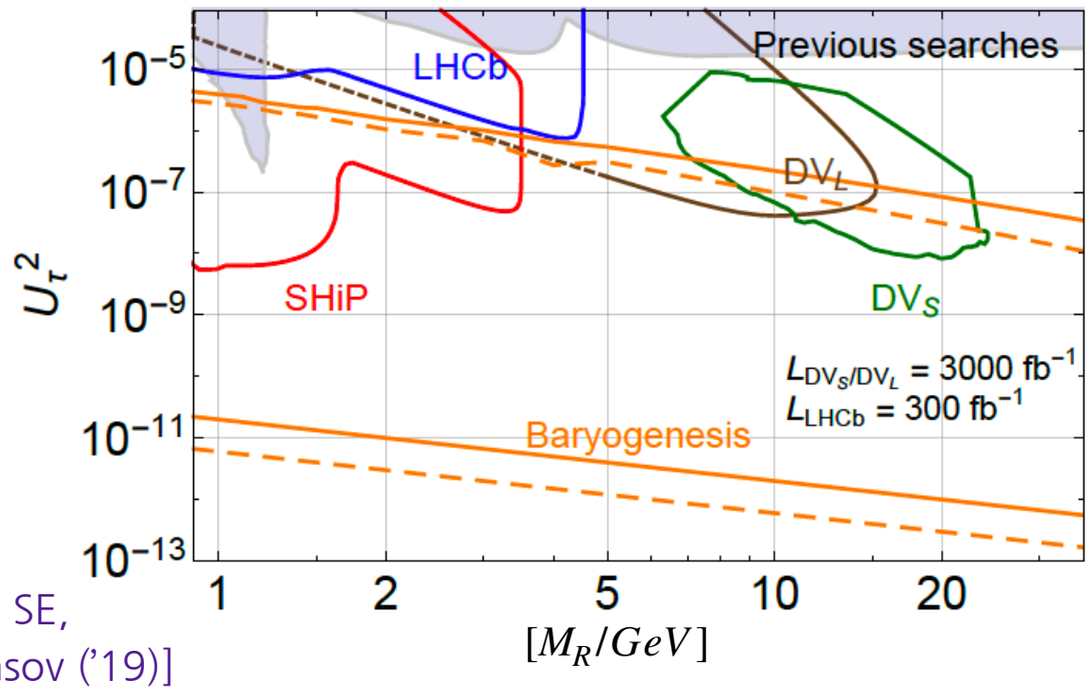
Optimized search for hidden sectors w/ D, B decays, e.g. SHiP

Predictions to Test the New Physics

The origin of neutrino oscillations and BAU can be probe experimentally.







[Boiarska, Bondarenko, Boyarsky, SE, Ovchynnikov, Ruchayskiy, Timiryasov ('19)]

Summary

Summary

ICRR theory group works on a variety of topic in cosmology and particle phenomenology.

Theorists suggest the new model beyond the SM and their verifiability.

- build new model [adding new symmetry/ particle/ interaction]

  Adding right-handed neutrinos, ν_R

- explain phenomena beyond the SM/ anomalies

  Neutrino mass through See-saw mechanism

  Baryon asymmetry of the Universe by Leptogenesis

- derive predictions in the new model

  Testability of GeV-scale ν_R