A cosmological sandwiched window for seesaw with primordial majoron abundance

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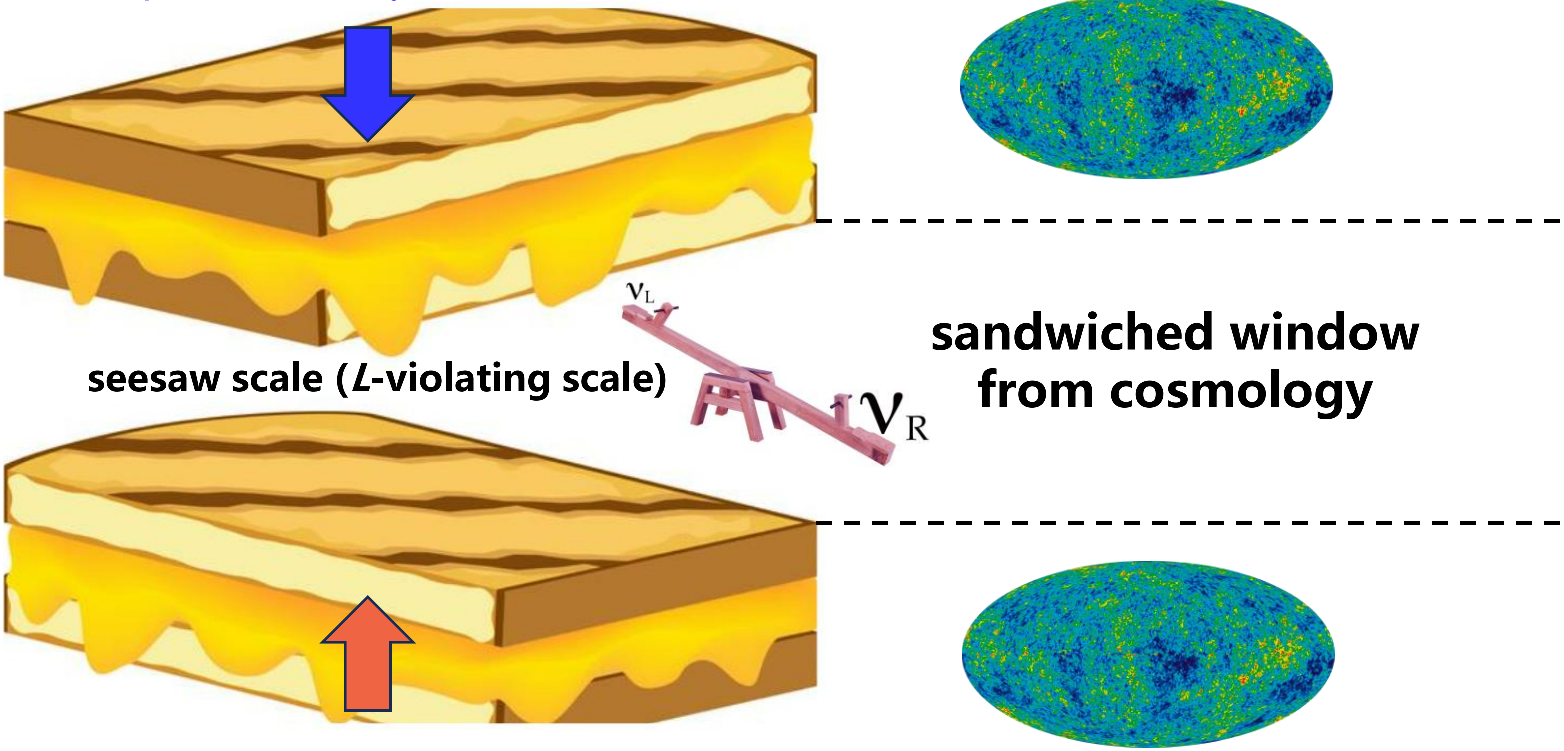
in collaboration with Shao-Ping Li

Main result

From CMB measurements on N_{eff}, the lepton-number breaking scale (seesaw scale) will be restricted into a "sandwiched window".



freeze-out
(from primordial majoron abundance)

seesaw scale (*L*-violating scale)

sandwiched window from cosmology

freeze-in
(from neutrino inverse decay)

Outline

- ☐ Framework
- ☐ Calculation of N_{eff}
- ☐ Sandwiched window from cosmology
- ☐ Conclusion

Framework

$S = (f + \rho + \mathrm{i}J)/\sqrt{2}$

$\langle S \rangle = f/\sqrt{2}$

- Singlet majoron model:

$$\mathcal{L} = -\overline{\ell_\mathrm{L}} Y_\nu \widetilde{\Phi} N_\mathrm{R} - \frac{1}{2} \overline{N^c_\mathrm{R}} Y_N N_\mathrm{R} S + \mathrm{h.c.}$$

Global $\mathrm{U}(1)_L$ symmetry: $L(\ell_\mathrm{L}) = L(N_\mathrm{R}) = +1$, $L(\Phi) = 0$, and $L(S) = -2$

- Majorana neutrino mass after $\mathrm{U}(1)_L$ spontaneous breaking: $M_\mathrm{R} = Y_N f/\sqrt{2}$

f = **lepton-number breaking scale** = **seesaw scale** [for $Y_N \sim \mathcal{O}(1)$]

seesaw relation: $m_\nu \sim Y_\nu^2 v^2/f$

- Goldstone of $\mathrm{U}(1)_L$ spontaneous breaking (majoron): $m_J = 0$

$m_J \neq 0$ when $\mathrm{U}(1)_L$ is broken explicitly

Majoron interacts with active neutrinos via (suppressed) flavor mixing

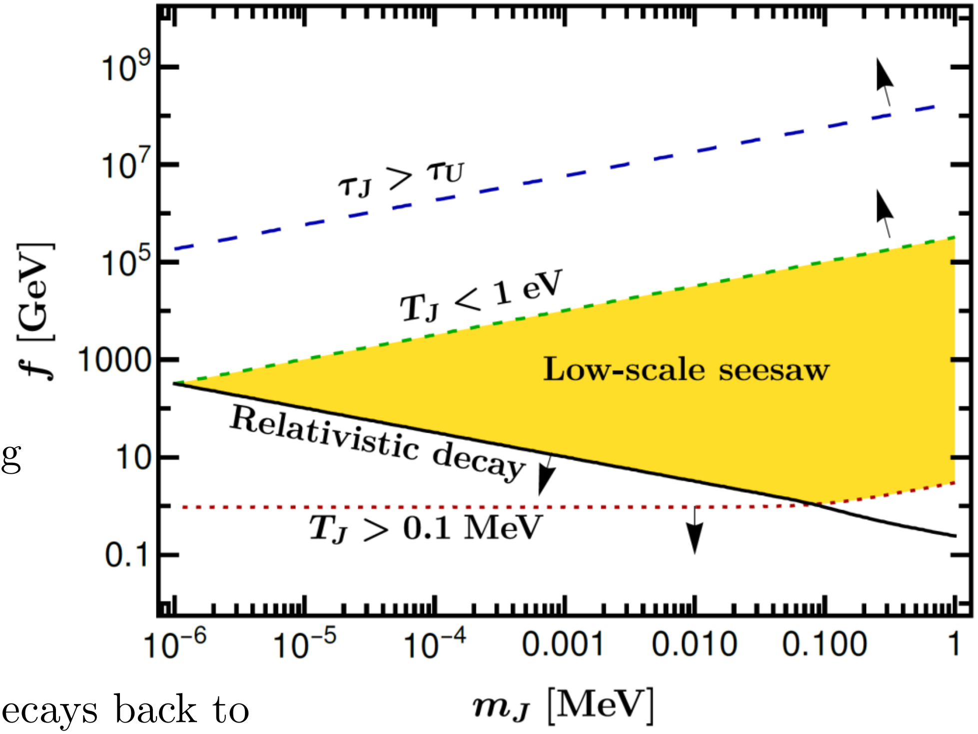
$$\mathcal{L}_{J\nu\nu} \simeq \frac{\mathrm{i}J}{2f} \sum_{i=1}^{3} m_i \overline{\nu_i} \gamma_5 \nu_i$$

Majoron cosmology

decaying temperature T_J defined by:

$$\tau_J^{-1} = \Gamma_J \simeq \Gamma_{J\to 2\nu} \equiv 2H(T_J)$$

- $f \gtrsim 10^{10}$ GeV, stable ⇒ majoron DM
- $f \lesssim 10^5$ GeV, decays before $T_{\rm eq} \simeq 1$ eV



relevant region in this work:

$$1 \text{ eV} \lesssim T_J \lesssim 0.1 \text{ MeV} \Leftrightarrow f \in [1, 10^5] \text{ GeV}$$

i.e., majoron decays after neutrino decoupling and before matter-radiation equality

majoron contributions to $\Delta N_{\rm eff}$:

- freeze-in: accumulated by $2\nu \to J$, then decays back to neutrinos $J \to 2\nu$. Smaller f ⇒ larger $\Delta N_{\rm eff}$
- freeze-out: primordial majoron abundance inherited from thermal equilibrium, then decays to neutrinos $J \to 2\nu$. For nonrelativistic decay, larger f ⇒ larger $\Delta N_{\rm eff}$

When two contributions coexist: f will be constrained from *both* directions ⇒ sandwiched window

Relativistic majoron decay

- The yield of majoron remains unchanged after freeze-out (at $T_{\rm fo}$):

$$Y^n_{J,\rm fo} \equiv \left.\frac{n_J}{s_{\rm SM}}\right|_{T=T_{\rm fo}} = \frac{45\zeta(3)}{2\pi^4 g_s(T_{\rm fo})}$$

- Relativistic majoron contribution to $N_{\rm eff}$ at BBN epoch:

$$\Delta N_{\rm eff}^{\rm BBN} = \left.\frac{\rho_J}{\rho_\nu^{\rm SM}}\right|_{T=T_{\rm BBN}} = \frac{4}{7}\left(\frac{g_{s,\rm BBN}}{g_{s,\rm fo}}\right)^{4/3}$$

- Relativistic majoron decay contribution to $N_{\rm eff}$ at CMB epoch:

$$\Delta N_{\rm eff}^{\rm CMB} = \left.\frac{\rho_{J\to 2\nu}}{\rho_\nu^{\rm SM}}\right|_{T=T_{\rm eq}} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{g_{s,\rm CMB}}{g_{s,\rm fo}}\right)^{4/3}$$

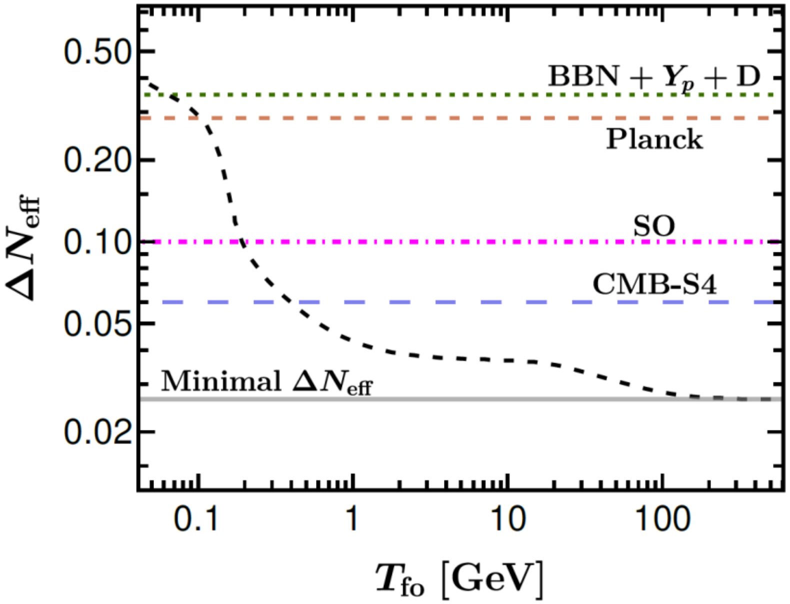
$\Delta N_{\rm eff}$ only depends on the freeze-out temperature $T_{\rm fo}$

$$\text{Planck}: \ \Delta N_{\rm eff} < 0.285$$

$$\text{BBN} + Y_p + \text{D}: \ \Delta N_{\rm eff} < 0.347$$

$$\text{SO}: \ \Delta N_{\rm eff} < 0.1$$

$$\text{CMB-S4}: \ \Delta N_{\rm eff} < 0.06$$



$T_{\rm fo} > 64$ MeV (BBN)

$T_{\rm fo} > 104$ MeV (Planck)

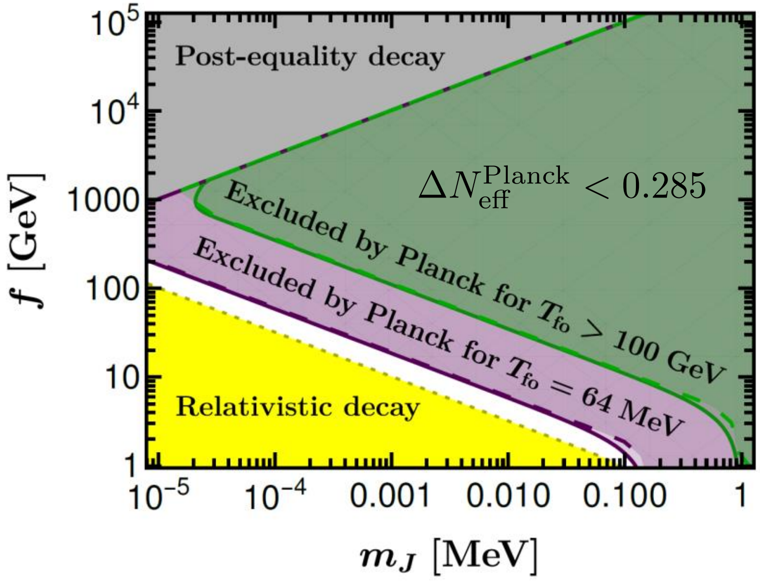
Nonrelativistic majoron decay

Boltzmann equations:

$$\frac{\mathrm{d}Y_J^n}{\mathrm{d}T} = \frac{\Gamma_J Y_J^n}{HT}\,, \qquad \frac{\mathrm{d}Y_\nu^\rho}{\mathrm{d}T} = -\frac{m_J \Gamma_J Y_J^n}{s_{\mathrm{SM}}^{1/3} H T}$$

Initial condition:

$$Y_{J,\mathrm{ini}}^n = Y_{J,\mathrm{fo}}^n = \frac{45\zeta(3)}{2\pi^4 g_s(T_{\mathrm{fo}})}$$



Contribution of NR decay to ΔN_{eff}:

$$\Delta N_{\mathrm{eff}} = \frac{\rho_{J\to 2\nu}}{\rho_\nu^{\mathrm{SM}}}\bigg|_{T=T_{\mathrm{eq}}} \simeq \frac{m_J Y_{J,\mathrm{fo}}^n s_{\mathrm{SM}}}{\rho_\nu^{\mathrm{SM}}}\bigg|_{T=T_J} \simeq 0.815\left(\frac{g_{s,T_J}}{g_{s,\mathrm{fo}}}\right)\left(\frac{m_J}{T_J}\right)$$

larger f (hence smaller T_J) and larger m_J lead to larger ΔN_{eff}

intuitively, $\rho_\nu^{\mathrm{SM}} \sim a^{-4}$, $\rho_J \sim a^{-3}$, so $\Delta N_{\mathrm{eff}} \sim \rho_J/\rho_\nu^{\mathrm{SM}} \sim a$

$f < 300$ GeV for $T_{\mathrm{fo}} = 64$ MeV

$f < 2$ TeV for $T_{\mathrm{fo}} > 100$ GeV

Freeze-in contribution

- Majoron abundance accumulated from neutrino inverse decay $2\nu \to J$

$$\frac{\mathrm{d}Y^n_{J,\mathrm{fi}}}{\mathrm{d}T} = -\frac{\mathcal{C}^n_{2\nu\to J}}{s_{\mathrm{SM}} H T} \qquad \text{initial condition: } Y^n_J = 0$$

collision term:

$$\mathcal{C}^n_{2\nu\to J} \simeq \frac{T_\nu m_J^3}{16\pi^3 f^2} \sum_{i=1}^{3} m_i^2 K_1(m_J/T_\nu)$$

- Majoron decay $J \to 2\nu$ contributes to ΔN_{eff}

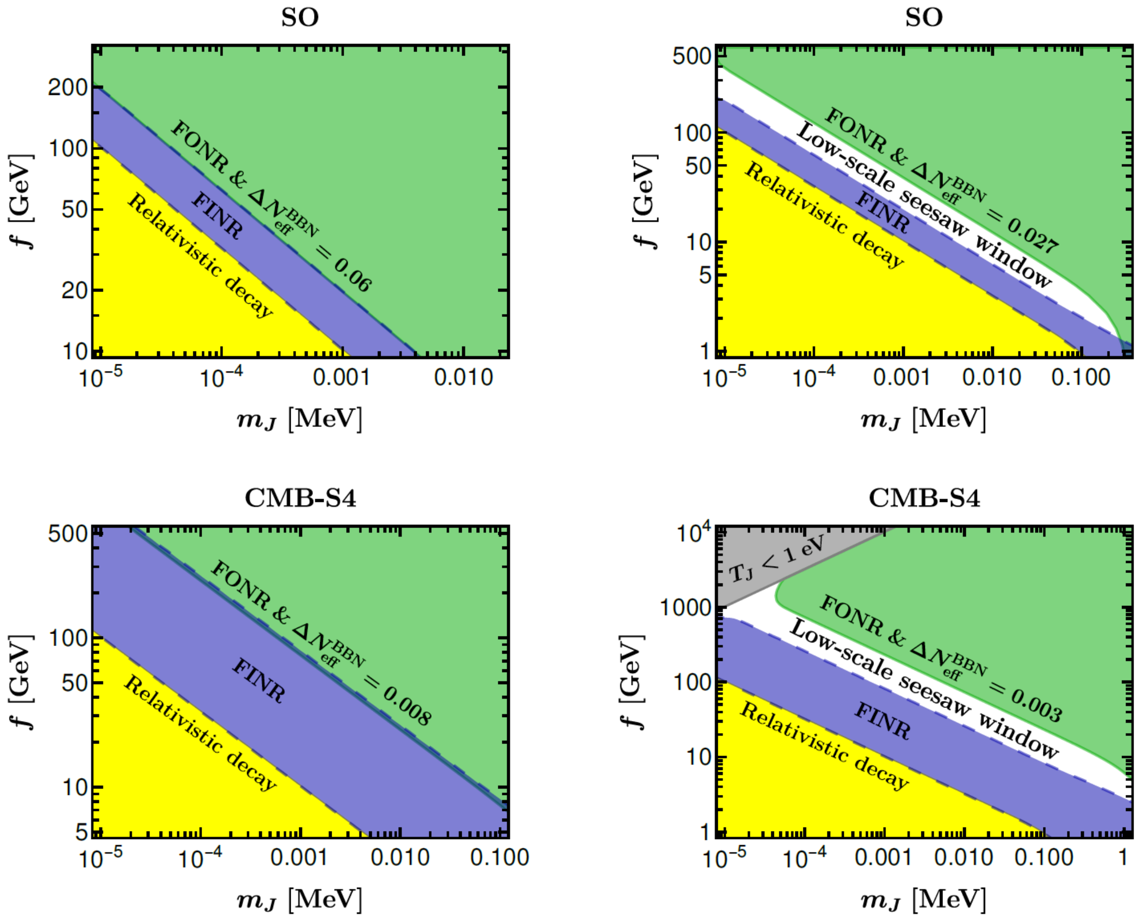
$$\Delta N_{\mathrm{eff}} \simeq \left. \frac{m_J Y^n_{J,\mathrm{fi}} s_{\mathrm{SM}}}{\rho_\nu^{\mathrm{SM}}} \right|_{T=T_J} \simeq 0.139 \left(\frac{\mathrm{MeV}}{m_J}\right)^{1/2} \left(\frac{\mathrm{GeV}}{f}\right)$$

smaller f (hence larger coupling) and smaller m_J lead to larger ΔN_{eff}

- Upper bound for ΔN_{eff} from freeze-in: $\Delta N_{\mathrm{eff}} \lesssim \mathcal{O}(0.1)$

Sandwiched window

$T_{\rm fo}/\mathrm{MeV}$	64	104	192	397	$> \mathcal{O}(10^5)$	—	—
$Y^{n}_{J,\rm ini}$	0.018	0.015	0.007	0.005	0.003	9×10^{-4}	3×10^{-4}
$\Delta N_{\rm eff}^{\rm BBN}$	0.347	0.285	0.100	0.060	0.027	0.008	0.003



Future CMB experiments:

$$\mathrm{SO}: \ \Delta N_{\rm eff} < 0.1$$

$$\text{CMB-S4}: \ \Delta N_{\rm eff} < 0.06$$

$$\Delta N_{\rm eff} = \Delta N_{\rm eff}^{\rm FO} + \Delta N_{\rm eff}^{\rm FI}$$

- freeze-out (FO) contribution: larger f and $m_J \Rightarrow$ larger $\Delta N_{\rm eff}$
- freeze-in (FI) contribution: smaller f and $m_J \Rightarrow$ larger $\Delta N_{\rm eff}$
- Both contributions exist: push f into a sandwiched window

larger primordial abundance
$\Rightarrow$ narrower window

Future CMB-S4 is able to completely close such a sandwiched window

Conclusion

- Current/future precision comsology is able to probe the lepton-number breaking scale and the mechanism for neutrino mass generation (complementary to collider searches).

- The primordial majoron abundance is important to constrain the lepton-number breaking scale f. In particular, for $m_J \in [10^{-6}, 1]$ MeV and $f \in [1, 10^5]$ GeV (i.e., low-scale seesaw scenario), it will be pushed into a "sandwiched window" by cosmology.

- Such a sandwiched window is a general phenomenon for any new light particle coupled to neutrinos/photons with abundances from both the UV and IR sources.

Thank you!

Q&A