Cosmology With a Very Light $L_\mu - L_\tau$ Gauge Boson

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SM + extra U(1) + "extra Higgs mechanism for $m_{Z'}$" ← outside of scope ; 2 TeV

	extra U(1) charge
L_1	0
L_2	+1
L_3	−1
E_1^c	0
E_2^c	−1
E_3^c	+1

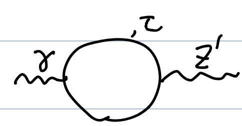
$$\mathcal{L}_{extra} = -\frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + Z'_{\mu} J^{\mu} ;$$

← eV − 100 MeV

(tree)

$$J^{\alpha} = g_{\mu-\tau} \left(\bar{\mu} \gamma^{\alpha} \mu + \bar{\nu}_\mu \gamma^{\alpha} P_L \nu_\mu - \bar{\tau} \gamma^{\alpha} \tau - \bar{\nu}_\tau \gamma^{\alpha} P_L \nu_\tau \right)$$

Kinetic mixing



$$\mathcal{L} \supset \varepsilon \sum_f \bar{f} \left(\underbrace{Q_f e}_{\text{EM couplings for fermion } f} Z'_\mu \gamma^\mu \right) f \quad \text{for } q \ll m_\mu$$

$$\varepsilon' = -\frac{e g_{\mu-\tau}}{12\pi^2} \log \frac{m_\tau^2}{m_\mu^2} \simeq -\frac{g_{\mu-\tau}}{70} \quad (\text{if no other extra particles.})$$

· $Z' \to ee$ μ

Z' : 5−20 MeV ; $g' = 10^{-4} - 10^{-3}$

- electron-phobic : less constrained.
- no gauge anomaly.
- solution to the muon g-2 problem.
- relax the discrepancy in Hubble constant.

Other solutions:

- SUSY with O(100)GeV ewkino → not found yet
- dark photon

  ... extra U(1) gauge boson

  with large kinetic mixing → excluded as a solution

  i.e. the same charge as photon

BABAR $ee \to \gamma A'$, $A' \to$ invisible

· discrepancy in H_0

Supernovae observation "current value" $H_0 = 73.52 \pm 1.62$) 3.6σ

Planck2018 + ΛCDM (standard cosmological model) $H_0 = 67.27 \pm 0.60$ km/s·Mpc best fit

→ ΛCDM should be extended?

ex. $N_{eff} = 3.046$ might be different? based on SM

$\Delta N_{eff} \sim 0.2$

Planck 2018 + ΛCDM + N_{eff} - varied $\begin{cases} N_{eff} = 3.27 \pm 0.15 \\ H_0 = 69.32 \pm 0.97 \end{cases}$

33% closer to supernovae (but yet 2.2σ)

Note: $\Delta N_{eff} \sim 0.5$ gives H_0 consistent but then "σ_8" has some discrepancy and thus not motivated.

$$\begin{cases} \rho_\gamma = \frac{\pi^2}{30} g_\gamma T_\gamma^4 & ; g_\gamma = 2 \\ \rho_\nu = \frac{\pi^2}{30} \frac{7}{8} g_\nu T_\nu^4 & ; g_\nu = 6 \text{ in SM}, \left(\frac{T_\nu}{T_\gamma}\right)^3 = \frac{4}{11} \text{ in SM} \end{cases}$$

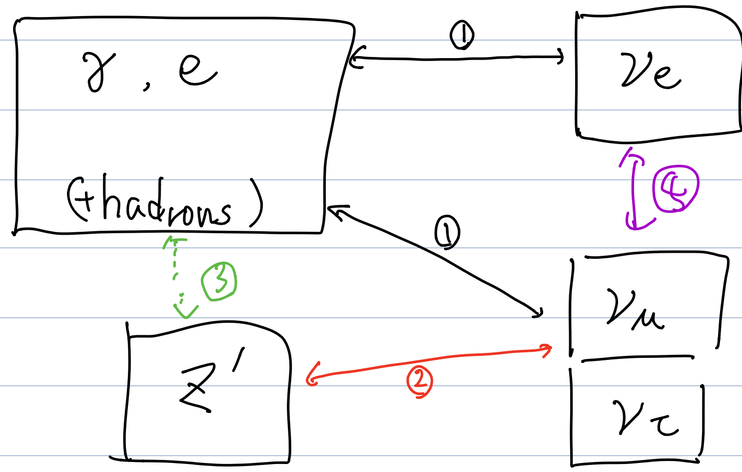
$$\Rightarrow \rho_\nu =: \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\, \rho_\gamma \quad \left[N_{eff} = \frac{g_\nu}{g_\gamma}\left(\frac{T_\nu/T_\gamma}{\sqrt[3]{4/11}}\right)^4 \right]$$

Two scenarios for $\Delta N_{eff} \sim 0.2$

- Early Universe equil. $g \gtrsim 4 \times 10^{-9}$; Z' in thermal bath (+ $(g-2)_\mu$-explanation)
  - → $m_{Z'} \sim 10$ MeV gives ΔN_{eff}.
- Freeze-in: $g' \lesssim 4 \times 10^{-9}$
  - → $m_{Z'} = 10^{-8}$ eV $-$ 10 MeV gives N_{eff}.

[1] Early-univ. equil. $g \gtrsim 4\times10^{-9}$, $m_{Z'} \sim 10\,\mathrm{MeV}$

· Universe at $T \sim 50\,\mathrm{MeV}$



①: $\nu\bar\nu \leftrightarrow e^-e^+$: equilibrium up to $T \gtrsim 3\,\mathrm{MeV}$

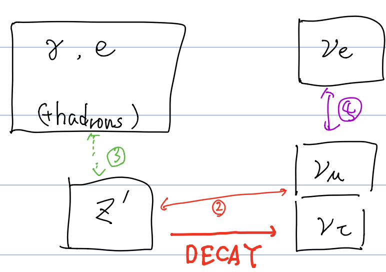
②: $Z' \leftrightarrow \nu_\mu\bar\nu_\mu, \nu_\tau\bar\nu_\tau$: " $T \gtrsim m_{Z'}/3$

③: $Z' \leftrightarrow e^+e^-$ due to kinetic mixing : less effective, but important

④: ν-oscillation effective at $T = 3\sim5\,\mathrm{MeV}$

Case A: $m_{Z'} \gtrsim 10\,\mathrm{MeV}$: ② decouples first. ··· no effect in the system

Case B: $m_{Z'} \lesssim 10\,\mathrm{MeV}$:



→ slower decrease of T_ν

⇒ Favors $m \sim 3\text{-}5\,\mathrm{MeV}$

$g = 10^{-6}$ — 10^{-3}

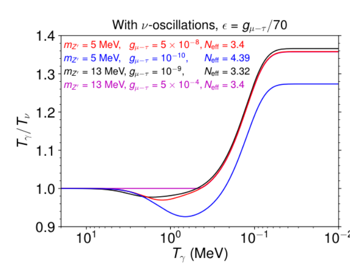
supernova 1987A cooling

$g-2$ if $(3-5)\times10^{-4}$

CCFR $\nu N \to \nu N \mu\mu$

Result v.s. literatures

- Kamada, Yu [1504.00711] ignores kin. mix. and uses wrong value of decoupling temperature of 1.5MeV.
- Kamada, Kaneta, Yanagi, Yu [1805.00651] includes kin. mix. but uses 1.5MeV and ignores SM nu-e interactions.



3 Freeze-in : $g_{\mu\tau} < 4\times10^{-9}$

Z' to be in thermal bath : $n_\mu \langle \sigma v \rangle_{\mu\mu\to\gamma Z'} > H$ holds before $T = m_\mu$

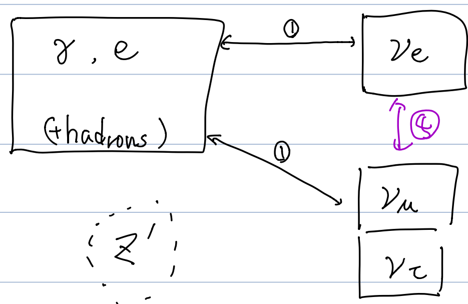
$$\Leftrightarrow g_{\mu-\tau} \gtrsim \left(\frac{1.66\sqrt{g_*}}{\alpha} \frac{m_\mu}{m_{pl}} \right)^{1/2} = 4\times10^{-9}$$

For $1.3\times10^{-10}\left(\frac{m_{Z'}}{\text{MeV}}\right)^{1/2} < g_{\mu-\tau} < 4\times10^{-9}$

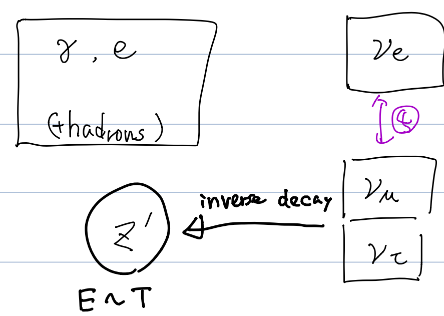
Z' is not in thermal bath but $\nu\bar{\nu}\to Z'$ produces $\mu^{Z'}_{eq}$

after ν-decouple but before $m_{Z'}$.

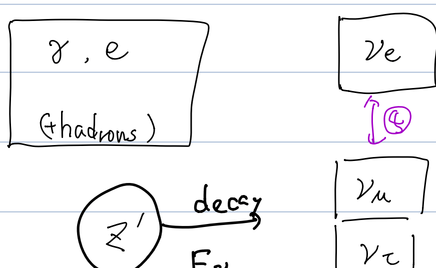
$T \gtrsim 3\,\text{MeV}$



$T < 3\,\text{MeV}$

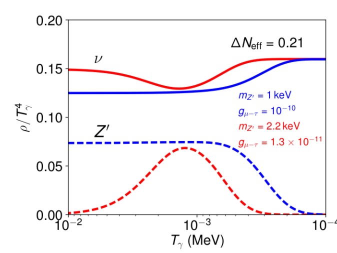


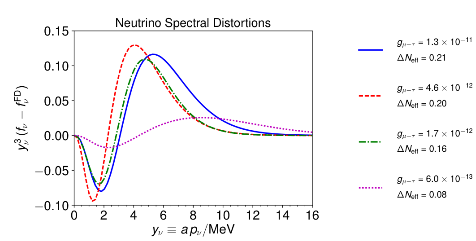
$T \sim m_{Z'}/3\sim5$

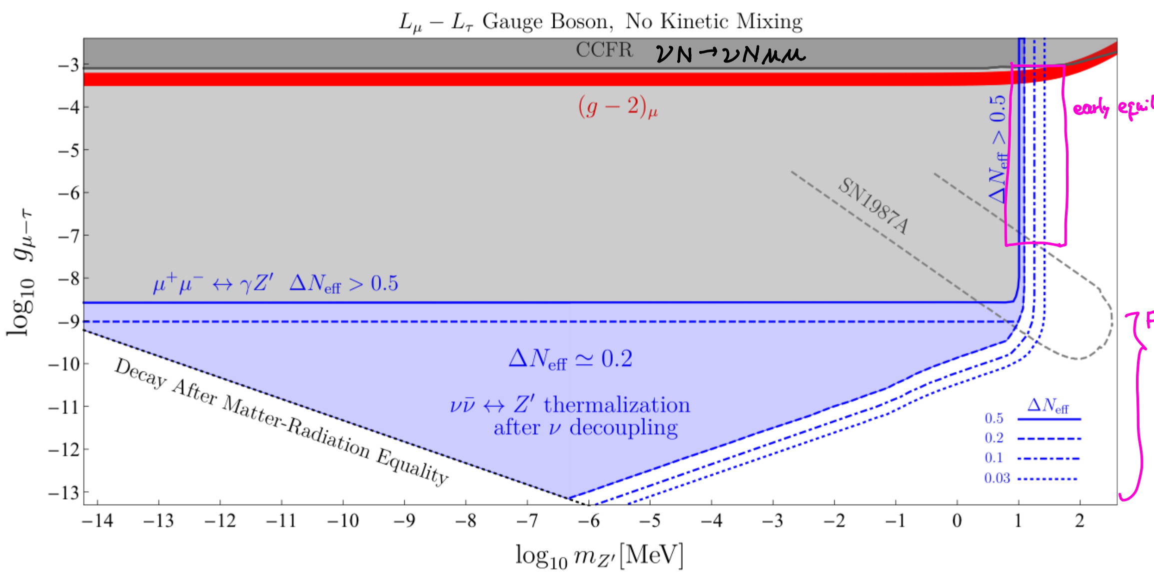


$\sim m_{Z'}/2 > T$

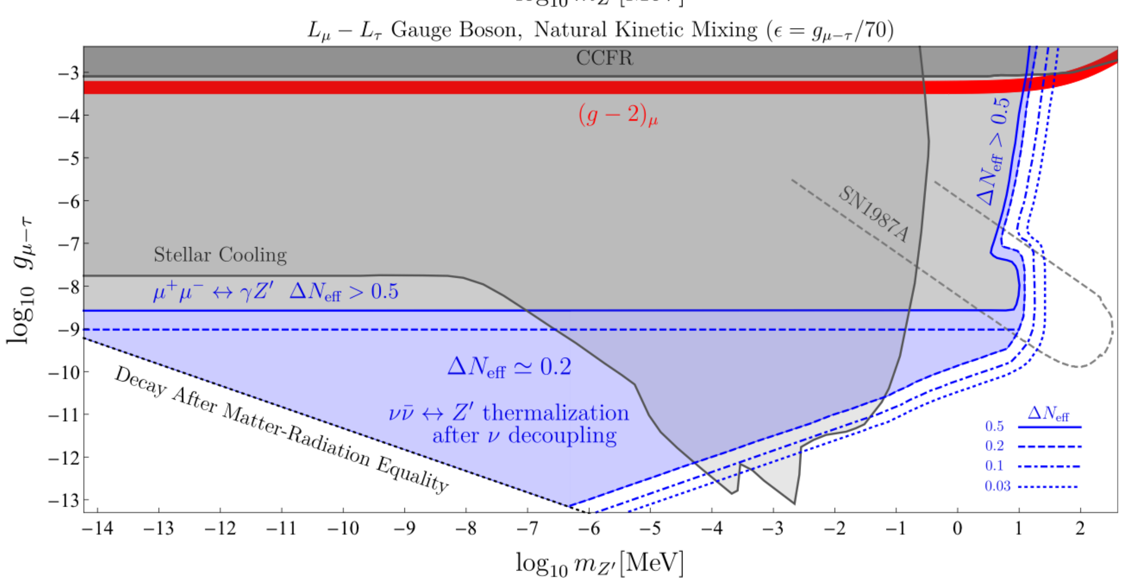
$\to$ larger N_{eff}.







$L_\mu - L_\tau$ Gauge Boson, No Kinetic Mixing
CCFR
$\nu N \to \nu N \mu\mu$
$(g-2)_\mu$
$\Delta N_{\rm eff} > 0.5$
early equil
SN1987A
$\mu^+\mu^- \leftrightarrow \gamma Z'$ $\Delta N_{\rm eff} > 0.5$
$\Delta N_{\rm eff} \simeq 0.2$
$\nu\bar{\nu} \leftrightarrow Z'$ thermalization
after ν decoupling
Decay After Matter-Radiation Equality
$\Delta N_{\rm eff}$
0.5
0.2
0.1
0.03
$\log_{10}\, g_{\mu-\tau}$
$\log_{10} m_{Z'}$[MeV]
Fre



$L_\mu - L_\tau$ Gauge Boson, Natural Kinetic Mixing ($\epsilon = g_{\mu-\tau}/70$)
CCFR
$(g-2)_\mu$
$\Delta N_{\rm eff} > 0.5$
SN1987A
Stellar Cooling
$\mu^+\mu^- \leftrightarrow \gamma Z'$ $\Delta N_{\rm eff} > 0.5$
$\Delta N_{\rm eff} \simeq 0.2$
$\nu\bar{\nu} \leftrightarrow Z'$ thermalization
after ν decoupling
Decay After Matter-Radiation Equality
$\Delta N_{\rm eff}$
0.5
0.2
0.1
0.03
$\log_{10}\, g_{\mu-\tau}$
$\log_{10} m_{Z'}$[MeV]