Dark radiation from the axino solution of the gravitino problem

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New observation opportunity for physics beyond the two standard models

- Bounds on ρ_{rad} given in terms of the effective number of neutrino species N_{eff} defined by

$$\rho_{\text{rad}} = \left(1 + N_{\text{eff}} \frac{7}{8} \left(\frac{T_\nu}{T_\gamma}\right)^4\right) \rho_\gamma \qquad \text{with } \frac{T_\nu}{T_\gamma} = \left(\frac{4}{11}\right)^{\frac{1}{3}}.$$

- Departure ΔN_{eff} from standard cosmology making use of the Standard Model parameterised as

$$N_{\text{eff}} = N_{\text{eff}}^{\text{SM}} + \Delta N_{\text{eff}} \quad \text{with} \quad N_{\text{eff}}^{\text{SM}} \simeq 3.$$

- ρ_{rad} affects expansion rate $\Rightarrow \Delta N_{\text{eff}}$ can be constrained.
- Independent measurements probing different cosmological times
  $\rightarrow$ might reveal time evolution of ΔN_{eff}
  $\neq$ increasing N_{eff} by, e.g., additional thermal species.

New observation opportunity to reveal an evolution of ΔN_{eff}

Current/ongoing observations

- ^{4}He formed ~ 1 s $\rightarrow$ big bang nucleosynthesis (BBN) lasts ~ 20 min

$$N_{\rm eff}^{\rm BBN} = 2.4 \pm 0.4 \quad (68\%\ \text{CL})^* \rightarrow \text{consistent with } N_{\rm eff}^{\rm SM}$$

- 100 ky later Universe becomes transparent for photons
  $\rightarrow$ cosmic microwave background (CMB) observed by ACT and WMAP:

$$(\text{CMB alone}) \quad N_{\rm eff}^{\rm CMB} = 5.3 \pm 1.3 \quad (68\%\ \text{CL})^\dagger \rightarrow \Delta N_{\rm eff} \sim 2.3$$

- using baryonic acoustic oscillations (BAO) and today's Hubble rate H_0:

$$(\text{WMAP+ACT+BAO+}H_0) \quad N_{\rm eff}^{\rm CMB} = 4.56 \pm 0.75 \quad (68\%\ \text{CL})^\dagger \rightarrow \Delta N_{\rm eff} \sim 1.5$$

$\Rightarrow$ everything consistent with $N_{\rm eff}^{\rm SM}$ $\rightarrow$ only hint of tension $\rightarrow$ Planck satellite
$\rightarrow \Delta N_{\rm eff} \simeq 0.26^\ddagger \Rightarrow$ 4- to 5-σ if current central values accurate!

Planck mission could turn hint into a discovery

* [Simha,Steigman, 08] consistent with earlier studies. Under discussion, see [Aver, Olive, Skillman, 10] & [Izotov, Thuan, 10].

† Atacama Cosmology Telescope (ACT) data analysis [Dunkley et al., 10] using WMAP7.

‡ [Perotto, Lesgourgues, Hannestad, Tu, Wong, 06] & [Hamann, Lesgourgues, Mangano, 08].

Dark radiation from invisible gravitino decay at the right time...

late emergence of visible radiation excluded $\rightarrow$ **dark** (decoupled) **radiation**

1) **Gravitino** $\Psi_{3/2}$ **inevitable** prediction of any local supersymmetric theory
2) Standard solution of the **strong CP problem**: Peccei-Quinn mechanism $\rightarrow$ introduces axion $a \xrightarrow{susy} \{a, \phi_{\rm sax}, \widetilde{a}\}$ with $\mathcal{L}_{\rm PQ} \propto 1/f_a$, where $f_a \gtrsim 10^9$ GeV

$\Rightarrow$ with $m_{\rm losp}{}^{*} \gtrsim m_{3/2} = \mathcal{O}\,(100\text{ GeV}) > m_{\widetilde{a}}$ gravitino decays invisibly

$$\Psi_{3/2} \rightarrow \widetilde{a} + a$$

with lifetime $\tau_{3/2}$ emitting relativistic axion and axino ($m_a \sim \mu$eV, $m_{\widetilde{a}} \ll m_{3/2}$)

$$t_{\rm BBN}^{\rm end} \sim 10^3\text{ s} < \tau_{3/2} \simeq 10^9\text{ s}\left(\frac{10^2\text{ GeV}}{m_{3/2}}\right)^3 < 5\times 10^{10}\text{ s} \simeq \tau_{\rm CMB}^{\rm max}{}^{\dagger}$$

Gravitino decays naturally at the right time

*LOSP = lightest ordinary supersymmetric particle = lightest particle in MSSM

† [Fischler, Meyers, 11]

...and with the "right" amount

$$\Delta N_{\rm eff} \simeq 0.6 \left(\frac{10^2\ \text{GeV}}{m_{3/2}}\right)^{\frac{5}{2}} \left(\frac{m_{\tilde{g}}}{1\ \text{TeV}}\right)^2 \left(\frac{T_R}{10^{10}\ \text{GeV}}\right) \to \mathcal{O}(1)\,!$$

1) $\Delta N_{\rm eff}(m_{3/2}, m_{\tilde{g}}, T_{\rm R})$ only $\to m_{3/2}, \tau_{3/2}(m_{3/2}),\ Y^{\rm tp}_{3/2}(m_{3/2}, m_{\tilde{g}}, T_{\rm R})$
2) gluino-gravitino mass gap natural for $m_{\rm losp} \gtrsim m_{3/2}$ (gravity mediation)
3) new upper bound on reheating temperature $T_{\rm R} \lesssim 10^{11}$ GeV $\to$ no upper bound from entropy production (dark radiation does not thermalize)

Thermal leptogenesis (consequence of see-saw mechanism): **origin of matter** with requirement $T_{\rm R} \gtrsim \mathcal{O}\left(10^{10}\ \text{GeV}\right) \to$ experimental input: light m_νs

4) $\Delta N_{\rm eff}, m_{\tilde{g}}$ might be measured soon $\Rightarrow m_{3/2}$ and $T_{\rm R}$ tightly constrained $\Rightarrow$ surprisingly **high testability!**

Thermal leptogenesis might predict an desired increase of $N_{\rm eff}$

LOSP decay...

LOSP (bino,Higgsino,stau,...)* $\rightarrow \widetilde{a} +$ SM particle $\Rightarrow$ **BBN constraints!**

- ✓ $\Delta N_{\text{eff}}^{\text{losp decay}} \ll 1$ and $\Omega_{\widetilde{a}}^{\text{losp decay}} \ll 1$
- ☹ early enough decay → possible mass bounds and upper bound on f_a

$$f_a \lesssim 10^{10}\ \text{GeV} \left(\frac{m_{\widetilde{B}}}{100\ \text{GeV}}\right)^{\frac{3}{2}} \left(\frac{\tau_{\widetilde{B}}^{\max}}{10^{-2}\ \text{s}}\right)^{\frac{1}{2}} \qquad (\widetilde{B} = \text{bino})$$

- ☺ wino/Higgsino LOSP $\rightarrow \tau^{\max} \sim (10^2\text{–}10^3)$ s
  $\rightarrow f_a > 10^{12}$ GeV and $m_{\text{losp}} \sim m_{3/2}$ allowed
- ☺ DFSZ dim-4 operators to $\widetilde{H}$-h and sfermion-fermion
  $\rightarrow f_a > 10^{12}$ GeV and $m_{\text{losp}} \sim m_{3/2}$ allowed

LOSP decay safe and allows for large f_a and $m_{\text{losp}} \sim m_{3/2}$

* bino: [Baer, Kraml, Lessa, Sekmen, 11]; stau: [Freitas, Steffen, Tajudddin, Wyler, 11]; Higgsino,wino,...: [this work] using [JH, Kersten, 11] & [Covi, JH, Pokorski, Roberts, 09]

...and dark matter

Three working scenarios:

1) **Natural cold axion dark matter**: $f_a \sim 10^{12}$ GeV $\to$ no bino LOSP and $m_{\tilde{a}} \sim \mathcal{O}\,(\text{keV})^*$ to avoid overproduction (model dependent production).
2) **Warm axino dark matter**: smaller $f_a \sim 10^{10}$ GeV $\Rightarrow \Omega_a \ll 1$ and $\Omega_{\tilde{a}}^{\text{ksvz}} > 1 \to \Omega_{\tilde{a}}^{\text{dfsz}} \sim \Omega_{\text{DM}}$ with $m_{\tilde{a}} > \mathcal{O}(\text{keV})$.
3) **Beyond LHC**: $f_a \gg 10^{12}$ GeV not forbidden with correspondingly heavier sparticles (not natural and more complicated) $\to$ beyond LHC discovery range $\to$ LHC can not exclude the scenario.

Natural cold axion (warm axino) dark matter

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*Axino mass model dependent. $\mathcal{O}\,(\text{keV})$ possible, e.g., [Tamvakis, Wyler, 82], [Goto, Yamaguchi, 92] & [Chun, Kim, Nilles, 92].

Conclusions and Outlook

ΔN_{eff} of $\mathcal{O}(1)$ after BBN for expected (natural) masses and T_{R} motivated by a completely disconnected notion (thermal leptogenesis)

- $\rightarrow$ $T_{\mathrm{R}} \lesssim 10^{11}$ GeV independent of PQ parameter space $\rightarrow m_{\widetilde{g}}/m_{3/2} > 1$ only
- ☺ gravitino problem “solved by” axino problem $\rightarrow$ solution of strong CP problem enabled $\rightarrow$ calls for more comprehensive studies
- ☺ no constraints from and on saxion* except Φ^{i}_{sax}
- ☺ natural cold axion (warm axino) dark matter $\rightarrow$ calls... studies
- ☺ thermal leptogenesis might predict a desired increase in N_{eff}

$\Rightarrow$ **Prediction from a consistent cosmology!**

- ☺ **High testability**: LHC$\rightarrow m_{\widetilde{g}}$, Planck$\rightarrow \Delta N_{\mathrm{eff}}^{\mathrm{CMB}} > 0 \Rightarrow$ gravitino problem a fortune $\Rightarrow$ ☺ $m_{3/2}$ tightly constrained $\Rightarrow T_{\mathrm{R}}$ as well

Even though $\Psi_{3/2}$ and $\widetilde{a}$ elusive and T_{R} experimentally not accessible $\rightarrow$ prediction testable with on-going experiments!

* as in [JH, Kersten, 11]

Thank you for your attention!

Hopefully, there are comments/questions?