Light Dark Matter and Dark Radiation

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Outlines

1. **Dark radiation**
2. **MeV-dark matter annihilation into neutrinos**
3. **Thermal equilibrium approximation**
4. **Out-of-equilibrium production**
5. **Conclusions**

Dark Radiation

- Radiation: relativistic particles and energy
- Cosmology : after neutrino decoupling $T_\gamma < 2 - 3 \text{ MeV } (t > 1sec)$

→ neutrinos and photons are relativistic

- In general, total radiation density

$$\rho_{\text{total}} = \rho_\gamma \left(1 + \frac{7}{8} \left(\frac{T_\nu}{T_\gamma} \right)^{4/3} N_{\text{eff}} \right)$$

Effective number of neutrino species

- Standard model of cosmology

$$\left(\frac{T_\nu}{T_\gamma} \right)_{\text{SM}} = \left(\frac{4}{11} \right)^{1/3}, \; N_{\text{eff}} \simeq 3.046$$

Planck Col., A&A 576, A16 (2014)

- CMB prediction : $N_{\text{eff}}^{\text{CMB}} \simeq 3.30 \pm 0.27 \quad (1\sigma)$
- BBN prediction : $N_{\text{eff}}^{\text{BBN}} \simeq 3.56 \pm 0.23 \quad (1\sigma)$ From He^4 measurements

G.Steigman, K.M. Nollet, arXiv:1401.5488.

$$\boxed{N_{\text{eff}} > N_{\text{eff}}^{\text{SM}}}$$

- Most of BSMs : considered extra relativistic species such as sterile neutrinos, Goldston bosons, etc

$$\frac{T_\nu}{T_\gamma} = \left(\frac{T_\nu}{T_\gamma}\right)_{\text{SM}}, \quad N_{\text{eff}} > N_{\text{eff}}^{\text{SM}}$$

In our scenario, we cosider DM annihilations are more heating neutrinos than photons, $Br_\nu > Br_\gamma$

$$\frac{T_\nu}{T_\gamma} > \left(\frac{T_\nu}{T_\gamma}\right)_{\text{SM}}, \quad N_{\text{eff}} = N_{\text{eff}}^{\text{SM}}$$

We parametrize N_{eff} w.r.t. SM temperature ratio $\left(\frac{T_\nu}{T_\gamma}\right)_{\text{SM}} = \left(\frac{4}{11}\right)^{1/3}$

$$\boxed{N_{\text{eff}} = N_{\text{eff}}^{\text{SM}} \left(\frac{T_\nu}{T_\gamma}\right)^{4/3} \left(\frac{11}{4}\right)^{4/3}}$$

In case that neutrinos are heated,

$$\boxed{N_{\text{eff}} > N_{\text{eff}}^{\text{SM}}}$$

We can compare this with experimental measurements.

Dark matter annihilation into neutrinos

Time evolution of Boltzmann equation of DM number density

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$

After neutrino decoupling, EM and DM (& neutrino) sectors are independent, not in thermal contact.

EM sector can always be in thermal equilibrium, because of their rapid interaction

$$\frac{dS_\gamma}{dt} = \frac{d(s_\gamma R^3)}{dt} = 0 \Rightarrow \frac{dT_\gamma}{dt} \simeq -HT_\gamma$$

Comoving number density $Y \equiv n/s_\gamma$

$$\frac{dY}{dx} = -\frac{\langle \sigma v \rangle s_\gamma}{xH}\left(Y^2 - Y_{eq}^2\right),$$

$x = M/T_\gamma$: inverse temperature

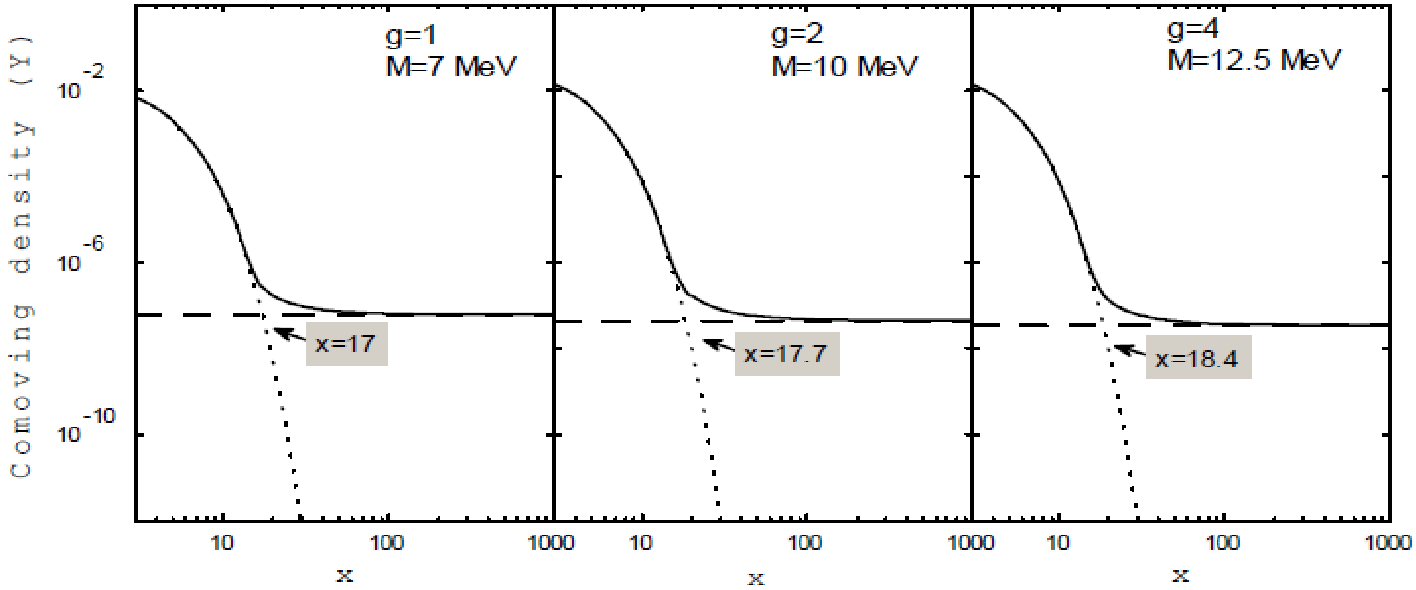

FIG. 1: Comoving number density ($Y \equiv n_{\rm DM}/s_\gamma$) as a function of inverse temperature ($x \equiv M/T_\gamma$) for $\langle \sigma v \rangle = 9.5 \times 10^{-26}\ cm^3/s$. The horizontal dashed line represents the correct relic density at present, and dotted line is the the equlilibrium number density.

Themal equilibrium approximation (entropy conservation)

- **Comoving entropy :** $S = sR^3 = \frac{2\pi^2}{45} g_{*s} T^3 \cdot R^3,$ $(S = S_\gamma \text{ or } S_\nu)$

$$\begin{array}{cc} \text{EM} & \text{DM (\&neutrino)} \\ \frac{(RT_\gamma)_f}{(RT_\gamma)_i} = \left(\frac{g^\gamma_{*s,i}}{g^\gamma_{*s,f}}\right)^{1/3}, & \frac{(RT_\nu)_f}{(RT_\nu)_i} = \left(\frac{g^\nu_{*s,i}}{g^\nu_{*s,f}}\right)^{1/3} \end{array}$$

From the common factor *R,* we get the relation between photon and neutrino temperatures

$$\frac{T_{\nu,f}}{T_{\gamma,f}} = \left(\frac{g^\nu_{*s,i}}{g^\nu_{*s,f}}\right)^{1/3} \left(\frac{g^\gamma_{*s,f}}{g^\gamma_{*s,i}}\right)^{1/3} \frac{T_{\nu,i}}{T_{\gamma,i}}$$

Initial conditions are taken from around neutrino decoupling time,

$$\frac{T_{\nu,i}}{T_{\gamma,i}} = \left(\frac{4}{11}\right)^{1/3} \quad \text{around this time}$$

Effective number of neutrino species

$$N_{\rm eff} = N_{\rm eff}^{\rm SM} \left(\frac{g^{\nu}_{*s,i}}{g^{\nu}_{*s,f}}\right)^{4/3} \left(\frac{g^{\gamma}_{*s,f}}{g^{\gamma}_{*s,i}}\right)^{4/3}$$

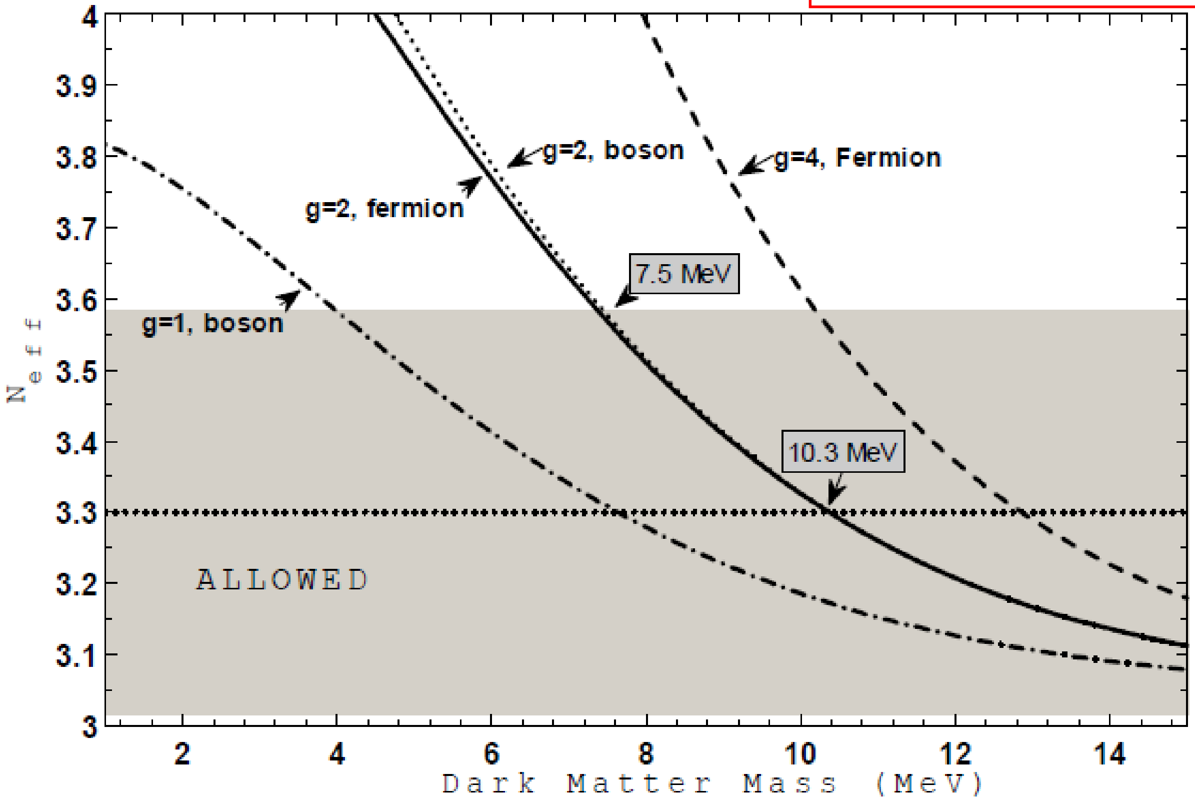

FIG. 2: The effective number of neutrino degrees of freedom, $N_{\rm eff}$, as a function of a thermal dark matter mass M. Curves correspond to a g=1 self-conjugate scalar (short dash), g=2 Majorana (solid), g=2 complex scalar (dotted) and g=4 Dirac dark matter (long dash). The horizontal band is the Planck CMB 1σ allowed range for $N_{\rm eff}$ and the horizontal dotted line is its central value.

Out-of-equilibrium production

DM annihilation transfers energy from the DMs to neutrinos.
From thermodynamics 2nd law, because of adiabatic expansion

Relativistic entropy production $dS = \frac{dQ}{T_\gamma} - -\frac{d\left(\rho_D R\right)}{T_\gamma}$

$$\rho_D R^3 \simeq n M R^3 = Y s_\gamma R^3,$$

$$\Downarrow$$

Production of entropy density

$$\Delta s = -M s_\gamma \int \frac{dY}{T_\gamma} = -s_\gamma \int \frac{dY}{x}$$

$$\swarrow$$

$$\boxed{\Delta g_* = -g_{*\gamma} \int \frac{dY}{x} \quad \Longrightarrow \quad N_{\text{eff}} = 3.046 + \frac{7}{4}\left(\frac{11}{4}\right)^{4/3} \Delta g_*}$$

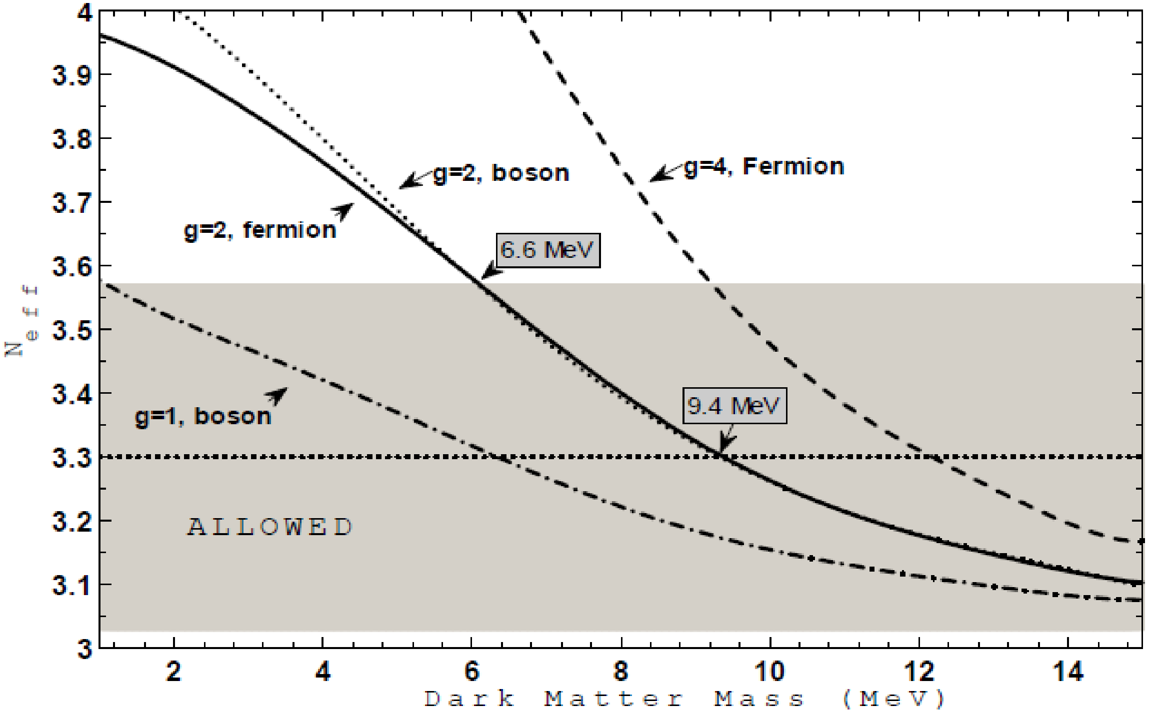

FIG. 3: The effective number of neutrino degrees of freedom, $N_{\rm eff}$, as a function of a thermal dark matter mass M. Curves correspond to a g=1 self-conjugate scalar (short dash), g=2 Majorana (solid), g=2 complex scalar (dotted) and g=4 Dirac dark matter (long dash). The horizontal band is the Planck CMB 1σ allowed range for $N_{\rm eff}$ and the horizontal dotted line is its central value.

Compared with results from thermal equilibrium approximation,
DR measurements can be explained for smaller DM masses,
⟶ longer annihilation time after neutrino decoupling and before freeze-out

Conclusions

- DR measurements were interpreted by light DM annihilation into neutrinos, and could be explained by this scenario.

- Quantitatively, I estimated the proper DM mass in DM thermal equilibrium approximation and out-of-equilibrium process.

- After neutrino decoupling, DMs have to annihilate longer time in out-of-equilibrium process. DMs have to be lighter.

THANKS for ATTENTION