Non-Thermal Production of Dark Matter as Dark Radiation

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What is Dark Radiation ?

Review

1. Bosons and Fermions contribute differently for the energy density

2. The energy density for relativistic species is proportional to T^4

3. The entropy density goes with T^3

4. Non-relativistic & heavy species do not contribute to the entropy

Energy Density

$$\rho = g_* \frac{\pi^2}{30} T^4$$

$$g_* = \sum_{i=bosons} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{i=fermions} g_i \left(\frac{T_i}{T}\right)^4$$

Entropy Density

$$\mathbf{s} = \frac{2\pi^2}{45} g_{*s} T^3$$

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What is Dark Radiation ?

Review

Photon-Neutrino Temperatures

Neutrinos decouple at ~1MeV. Electron-positrons went out of equilibrium about at the same temperature. Comparing the entropy densities before and after the e+e- annihilations we find:

$$s(a(t_{before})) = \frac{2\pi^2}{45}\left[g_\gamma + \frac{7}{8}(g_e + g_{e^+} + 3g_\nu + 3g_\nu)\right]T_1^3$$

$$s(a(t_{after})) = \frac{2\pi^2}{45}\left(2T_\gamma^3 + \frac{7}{8}6T_\nu^3\right)$$

Using the entropy conservation:

$$\frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{\frac{1}{3}}$$

What is Dark Radiation ?

Standard Cosmological Model

$$\rho_{rad} = \rho_\gamma + \rho_\nu = [1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}]\rho_\gamma$$

In general

$$\rho_{rad} = \rho_\gamma + \rho_\nu = [1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} (N_{eff} + \Delta N_{eff})]\rho_\gamma$$

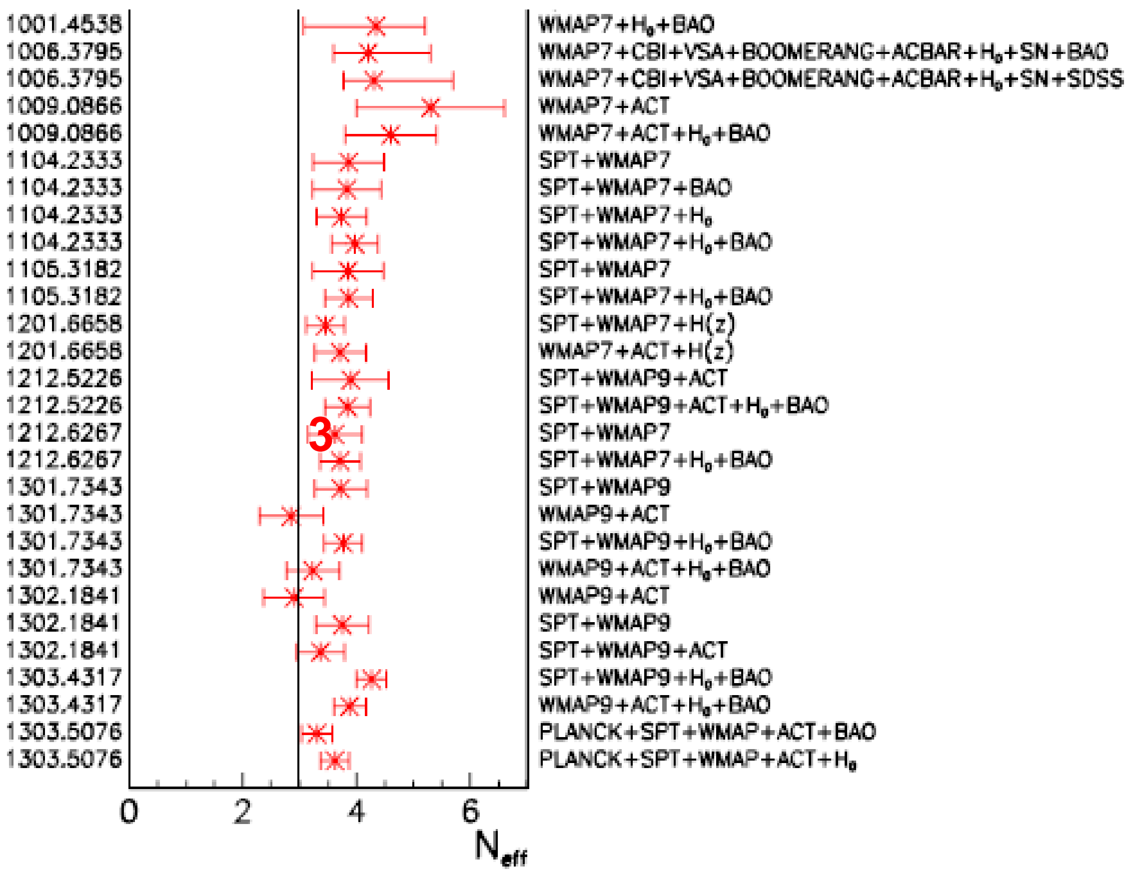
Dark Radiation is parametrized in terms of the number of effective neutrinos Neff

Leave your bias aside regarding dark radiation for a moment....

Dark Radiation Status

Planck finds no evidence for Dark Radiation, but...

DATA



"We find H_0 discrepant with the direct measurement at the 2.2σ level".
Planck Collaboration

"Since Neff is positively correlated to H_0 the tension Between Planck and direct measurements of H_0 in the base ΛCDM model can be reduced at the expense of high Neff".
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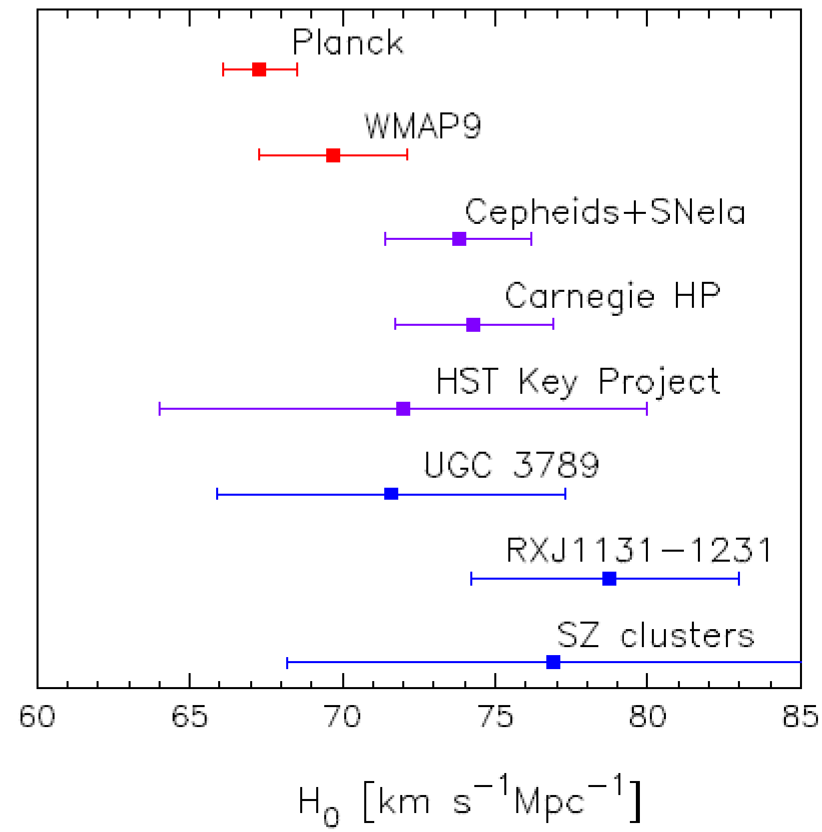
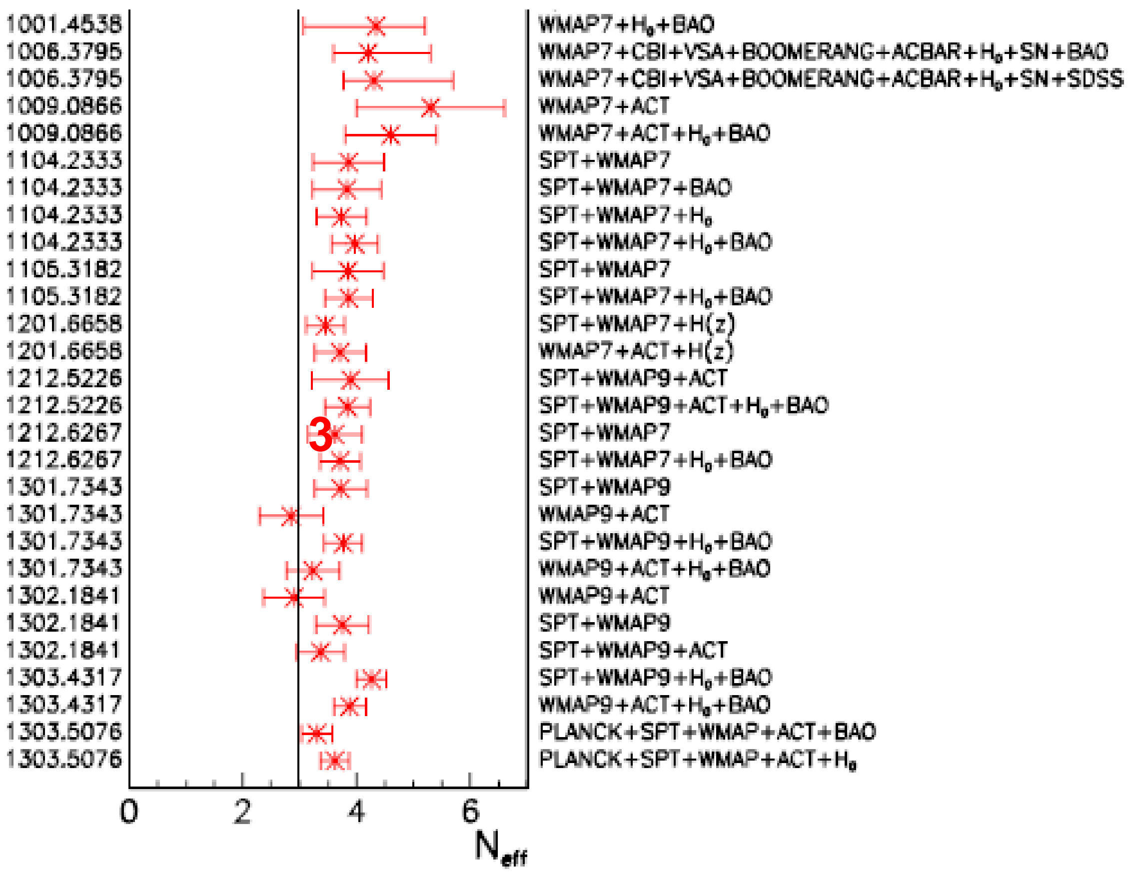


Dark Radiation Status

Planck finds no evidence for Dark Radiation, but...

Being conservative....

We can interpret the data either as an evidence for dark radiation or as way to constrain models where this dark radiation scenario rises.



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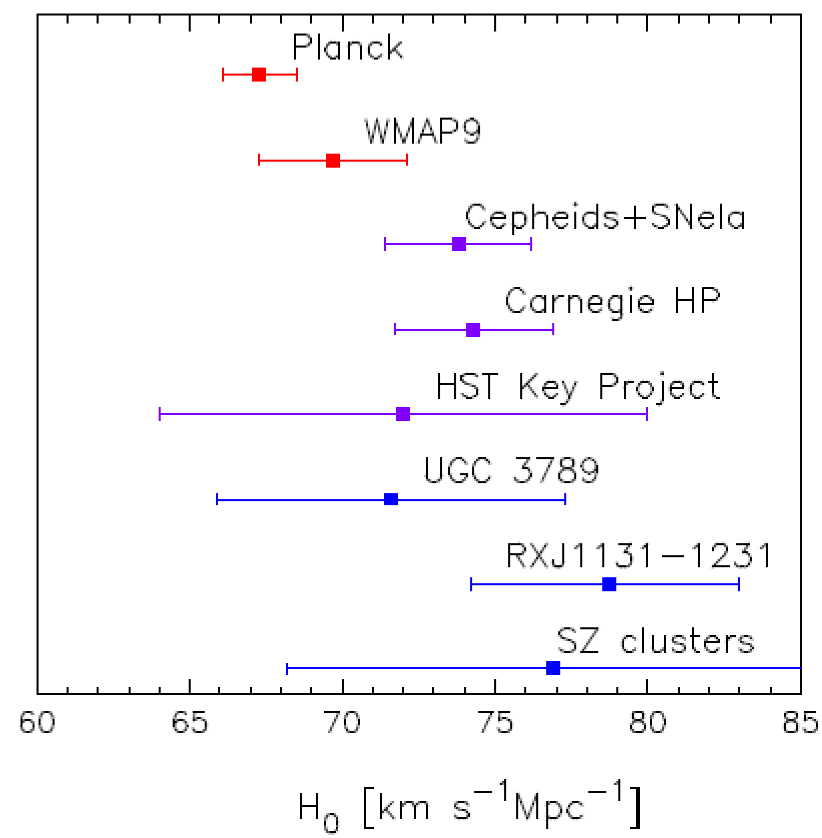


Evidences for Dark Matter

Galaxy Rotation Curves

Structure Formation

Nucleosynthesis

Variety

Power of the Dark Matter Hypothesis!!

CMB

Gravitational Lensing

Bullet Cluster

Evidences for Dark Matter

Galaxy Rotation Curves

Structure Formation

Nucleosynthesis

CMB

Dark Matter Hypothesis is as powerful as He man!!!

Gravitational Lensing

Bullet Cluster

Evidences for Dark Matter

Galaxy Rotation Curves

PAMELA/AMS02 ?

Structure Formation

DAMA ?

CoGeNT ?

Nucleosynthesis

CMB

Gamma ray line?

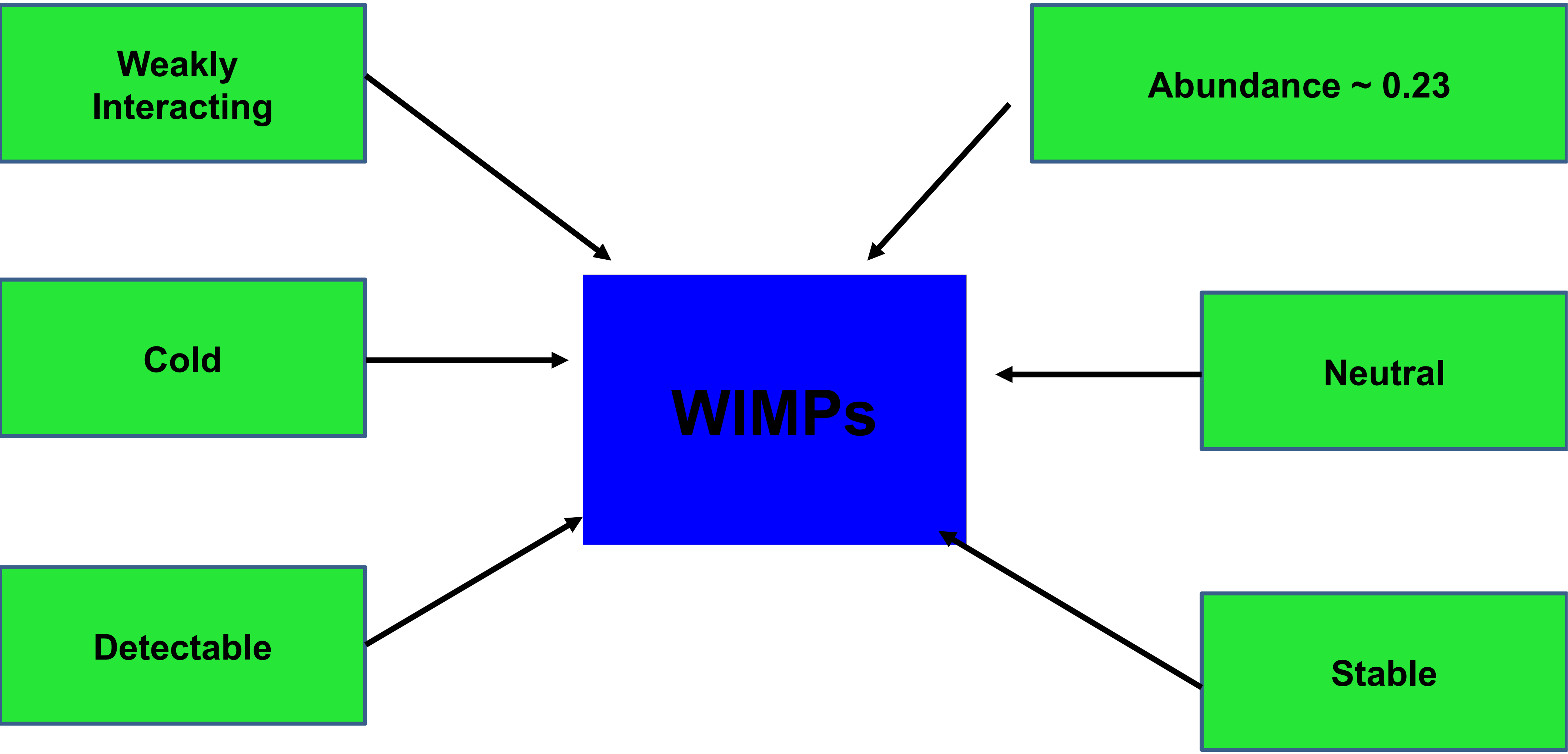
CDMSII ?

Gravitational Lensing

Galactic Center excess?

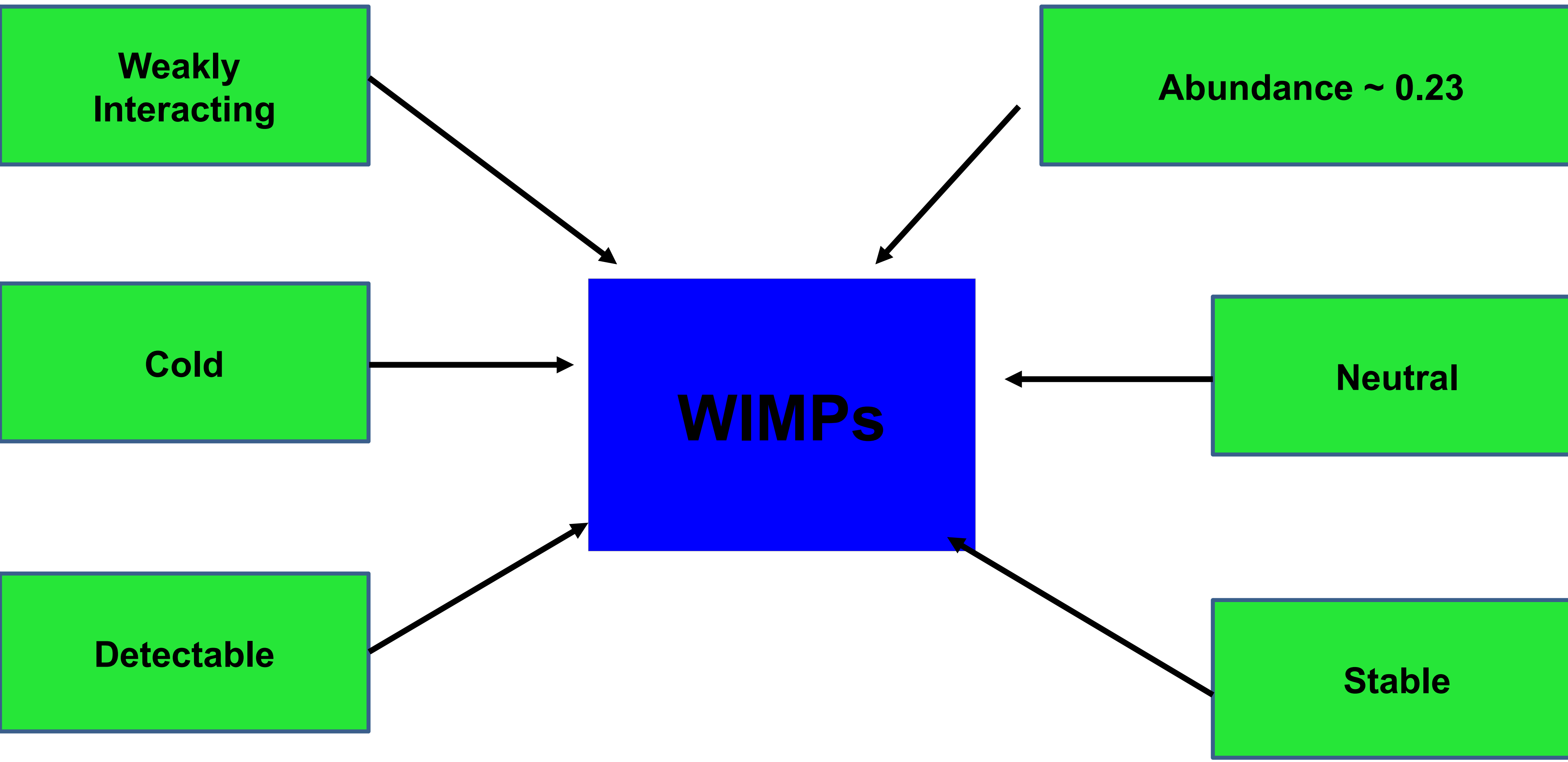
Bullet Cluster

WIMPs



Weakly Interacting
Abundance ~ 0.23
Cold
WIMPs
Neutral
Detectable
Stable

WIMPs



WIMPs are thermally produced

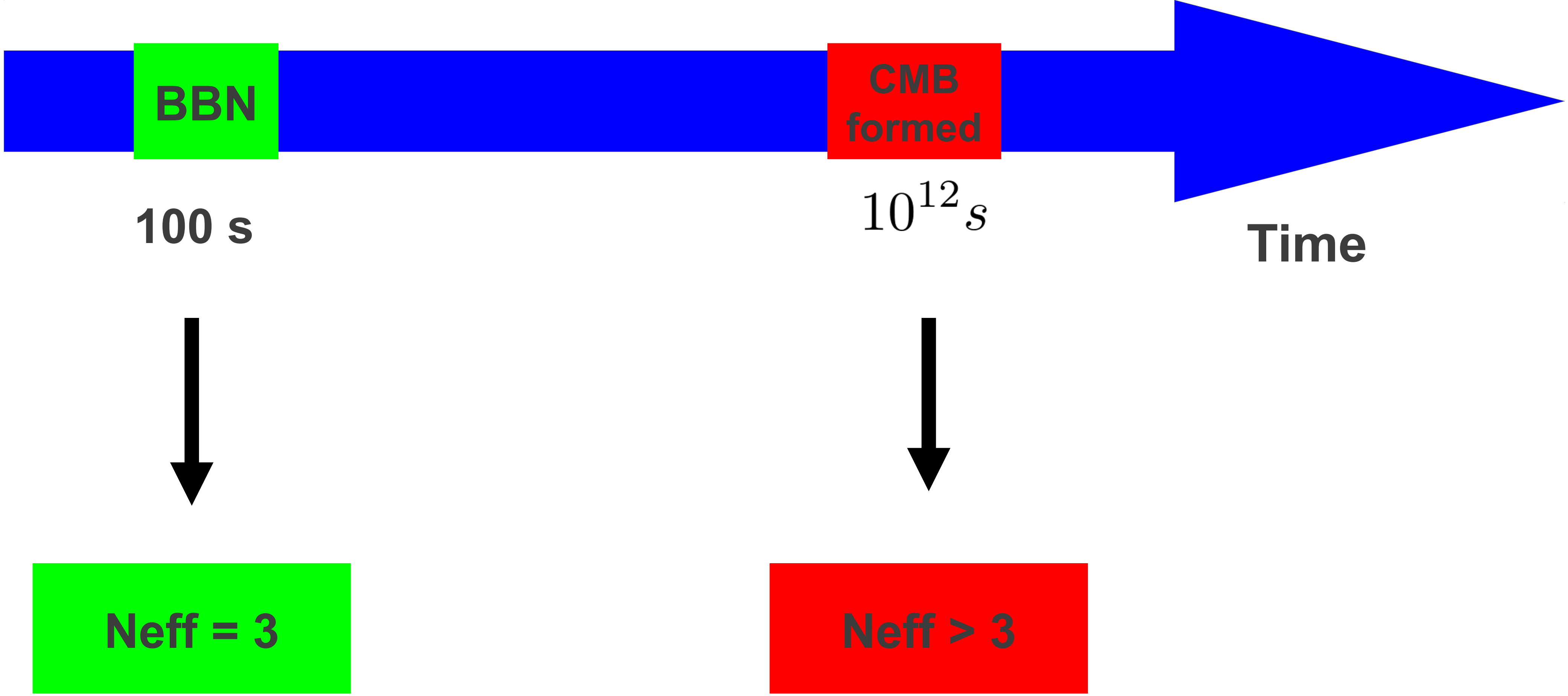
What if ?

Some fraction of the WIMPs had a non-thermal origin

Why Should we care?

1.Because non-thermally produced Dark Matter particles can mimic the effect of one neutrino species in the early universe

2. It can explain why BBN obtain $N_{eff} = 3$ while precise measurements of the CMB find $N_{eff} > 3$.



Why are they different ?

BBN

100 s

CMB formed

$10^{12} s$

Time

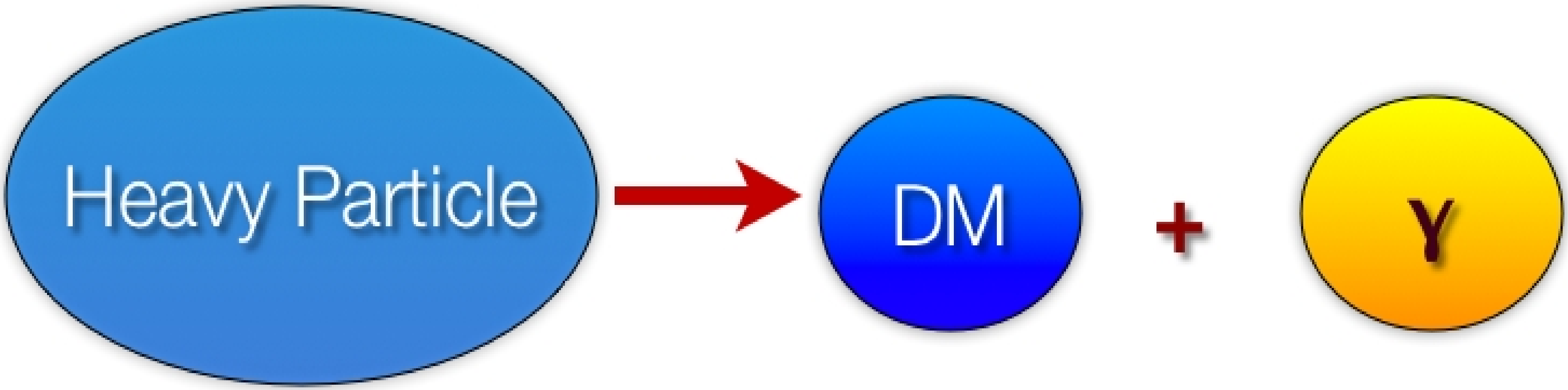
Neff = 3

Neff > 3

Is Skeletor responsible ? **Maybe!**

Non-thermal production of WIMPs might explain this difference!

Idea



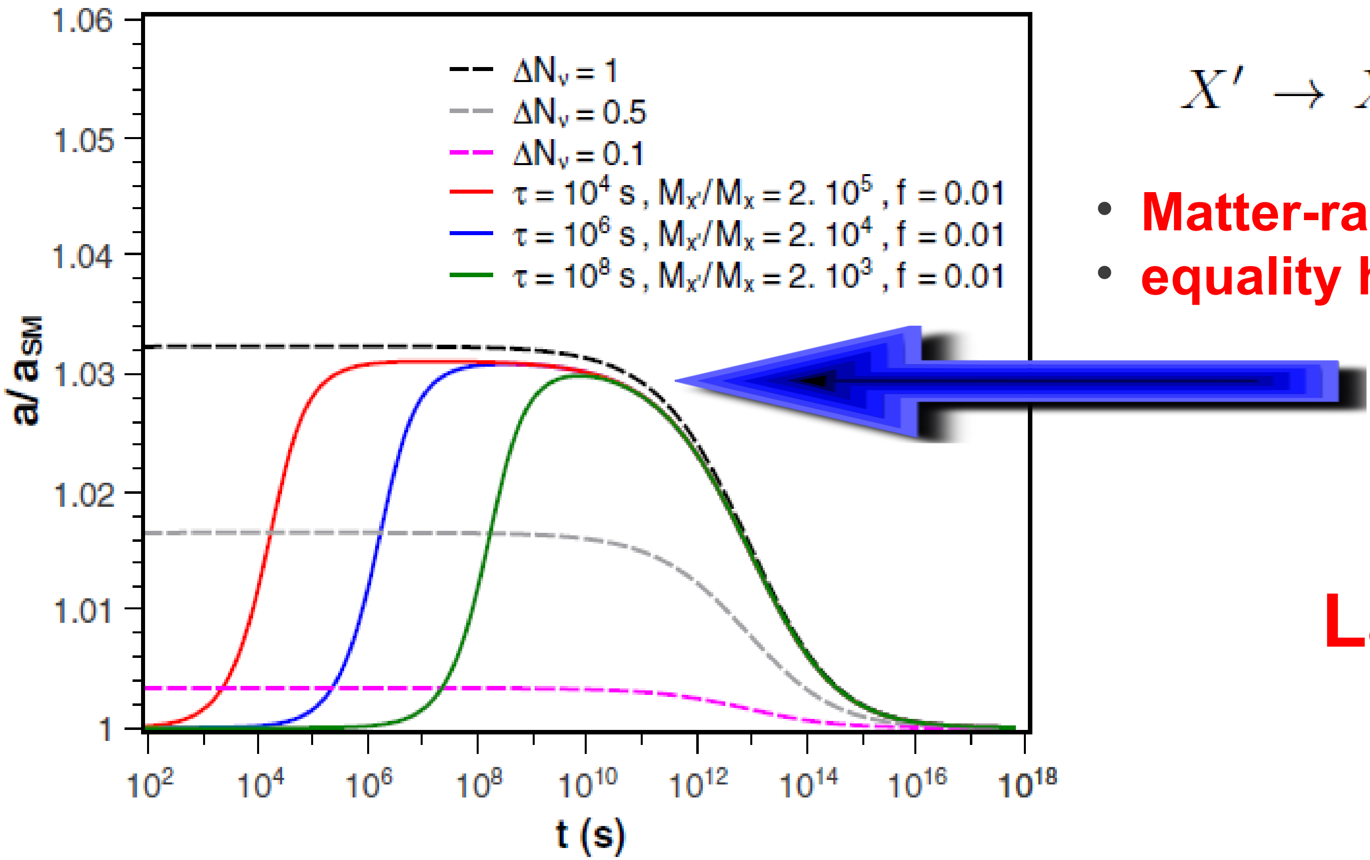
→ **Mass ratio between the mother and the DM particle**

→ **Lifetime of the mother particle**

→ **Fraction (f) of Dark Matter particles produced non-thermally**

$$\Delta N_{eff} \simeq 4.87 \cdot 10^{-3} \left(\frac{\tau}{10^6\ s}\right)^{1/2} \times \left[\left(\frac{M_{X'}}{2M_{DM}} + \frac{M_{DM}}{2M_{X'}} - 1\right)\right] f.$$

Non-thermally produced Dark Matter particles can mimic one neutrino species in the early universe, Neff ~ 4!



$$X' \to X + \gamma$$

- **Matter-radiation**
- **equality happens**

Large mass ratio!!

a → Scale factor of the Universe of our model
a_{SM} → Scale factor in the Standard Model

Structure Formation Bounds

DM particles with large kinetic energies would not cluster at sufficiently small scales due to free-streaming.

This slowing down the growth of structures would wash out matter density fluctuations.

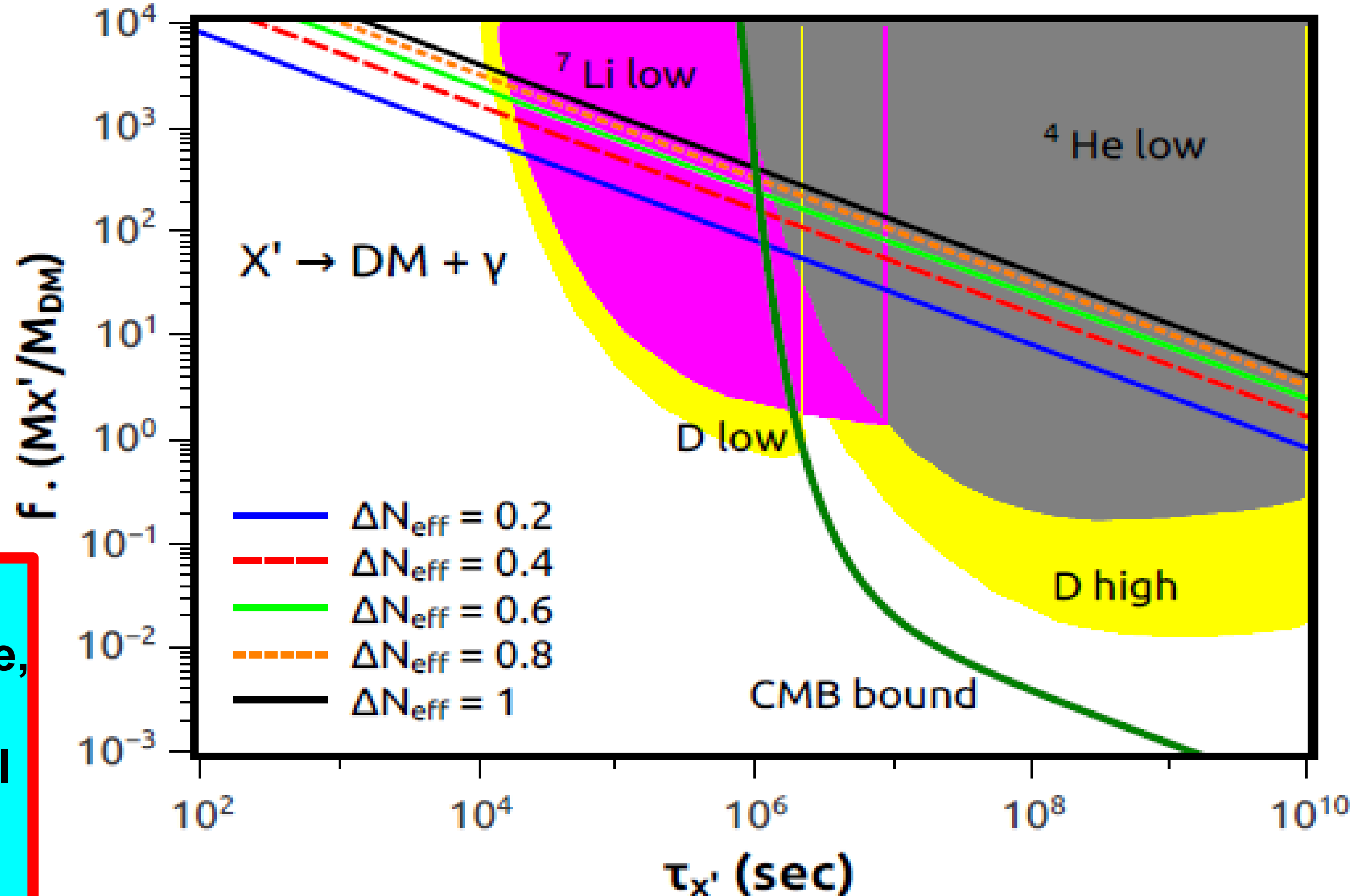
All dark matter particles could not be relativistic at the matter-radiation equality.

<1% of the dark matter particles may have had a non-thermal origin!

BBN and CMB bounds

We need

1. **Large mass ratios**
2. **Short lifetime < 10^4 s**



Energy releases which occur long after BBN may, in principle, spoil the successful BBN predictions for light elemental abundances.

(Double) Compton scattering thermalize high energy photons for t < 10^3 s

These processes become inefficient for t > 10^4 s changing the photon spectrum.

Our goal is to check what kind of effective operators this Dark Radiation Scenario is realized while obeying CMB, BBN and Structure formation bounds

Model 1. Mother particle is a Scalar

$$\mathcal{L}_{eff} = \frac{1}{\Lambda} B_\mu (\partial_\nu S) F^{\mu\nu}$$

Model 2. Mother particle is a Boson

$$\mathcal{L}_{eff} = g W_\mu B_\nu F^{\mu\nu}$$

Model 3. Mother particle is a Fermion

$$\mathcal{L}_{eff} = \frac{1}{\Lambda} \left(\bar{\psi}\, \sigma_{\mu\nu}\, \chi \right) F^{\mu\nu}$$

Model 4. Mother particle is a pure Bino

$$\mathcal{L} = \frac{-i}{8\pi M_\star} \tilde{G}_\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu \tilde{B}^\mu F_{\nu\rho}$$

Model 4. Bino/Gravitino Scenario

$$\mathcal{L} = \frac{-i}{8\pi M_\star}\tilde{G}_\mu[\gamma^\nu,\gamma^\rho]\gamma^\mu\tilde{B}^\mu F_{\nu\rho}$$

Input

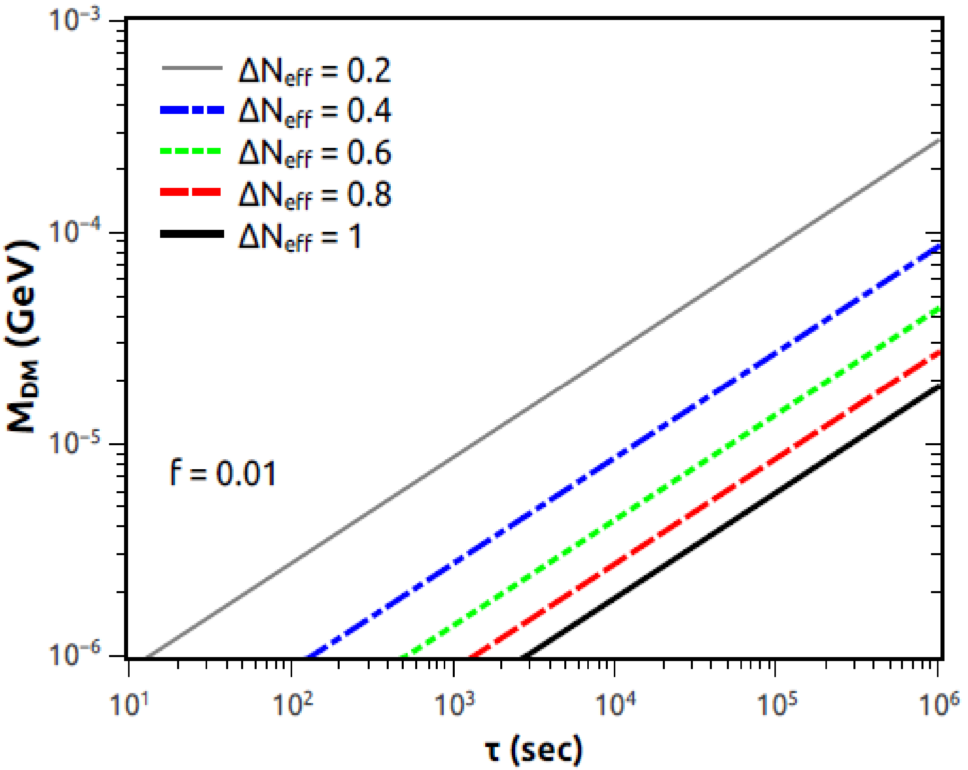
1. In low scale supersymmetry breaking models the Bino is much heavier than the Gravitino

2. Lifetime $$\tau(\tilde{B}\to\gamma\tilde{G}) \simeq 750\ \mathrm{s}\left(\frac{M_{\tilde{G}}}{1\ \mathrm{keV}}\right)^2\left(\frac{1\ \mathrm{GeV}}{M_{\tilde{B}}}\right)^5$$

3. Just a small fraction of the Gravitinos are Non-thermally produced

Bound on the Gravitino Mass

$$M_{\tilde{G}} \lesssim (4\ \mathrm{MeV})\left(\frac{\tau}{10^4}\right)^{1/2}\left(\frac{f}{\Delta N_{eff}}\right)^{5/3}$$



KeV gravitinos may account for the Neff ~ 1 while stilll evading BBN, CMB and Structure Formation bounds!

Is it possible to have a 10 GeV WIMP as Dark Radiation ?

What about a 100 GeV WIMP as Dark Radiation ?

Yes to both!
Result coming soon!!!

Conclusions

It is worthwhile bounding particle physics
Models where the dark radiation setup is present

Non-thermal production of WIMPs at 1% level
can mimic one neutrino species in the early universe (N_{eff} ~1)

Lower mass bounds were obtained on the mass of the WIMP for
effective models and a Supersymmetric model
(Bino-Gravitino scenario).

In summary....can we build models where this dark radiation scenario is realized ?

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Backup Slides

Production of Gravitinos-Reheating Temperature

Thermally production of Gravitinos implies

$$\frac{T_R}{100\ \mathrm{GeV}} \simeq \left(\frac{\Omega_{\tilde{G}} h^2}{0.2}\right)\left(\frac{1\ \mathrm{keV}}{M\tilde{G}}\right)$$

Bound on the reheating temperature

Therefore, to avoid over-closing the universe we need reheating temperatures at 1TeV if case of ~10KeV Gravitinos.