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Quark–gluon plasma as the possible source of cosmological dark radiation

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Abstract

The effective number of neutrinos, N_{eff}, obtained from CMB fluctuations accounts for all effectively massless degrees of freedom present in the Universe, including but not limited to the three known neutrinos. Using a lattice-QCD derived QGP equation of state, we constrain the observed range of N_{eff} in terms of the freeze-out of unknown degrees of freedom near to quark–gluon hadronization. We explore limits on the coupling of these particles, applying methods of kinetic theory, and discuss the implications of a connection between N_{eff} and the QGP transformation for laboratory studies of QGP.

Outline of the talk

1. Introduction:
   - CMB fluctuation analysis 'observes' N_ν, number of invisible Cosmic Neutrinos pushing the Universe apart
   - Anything else out there adding to the pressure?
2. Impact of 'Darkness'[1] on N_ν
   - Darkness sourced at QGP Phase Transition: 'reheating' after cosmic hadronization reduces δN_ν to near CMB sensitivity limits.
   - Limits on coupling for such new particles: dark light Goldstone Bosons could be visible in laboratory QGP experiments.
3. Laboratory Signature of Darkness and NA61

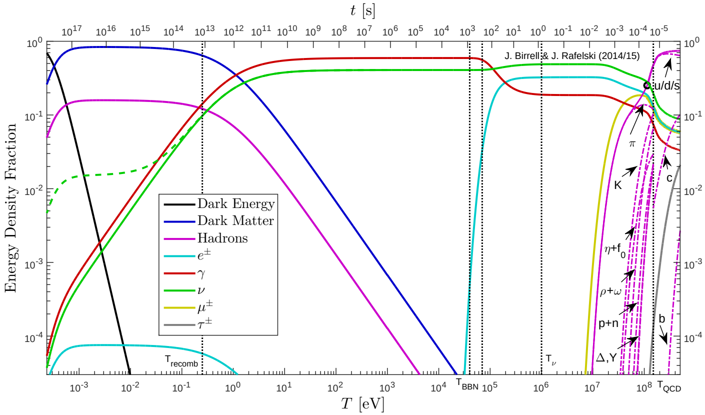
[1] Undiscovered and nearly massless particles, not dark matter

Relic Neutrino Background:

At a temperature of 5 MeV the Universe consisted of $e^{\pm}$-pairs, photons, and neutrino plasma. At around 1 MeV neutrinos stop interacting or freeze-out and free stream through the universe. Today they comprise the relic cosmic neutrino background (CNB).

Direct measurement:
Relic neutrinos have not been directly measured.

Indirect measurement:
Impact on speed of Universe expansion can be seen in the CMB. This constrains neutrino mass and number of invisible relativistic degrees of freedom dominated by cosmic neutrinos.


t [s]
J. Birrell & J. Rafelski (2014/15)
Energy Density Fraction
T [eV]
Dark Energy
Dark Matter
Hadrons
e±
γ
ν
μ±
τ±
T_recomb
T_BBN
T_ν
T_QCD
u/d/s
π
K
c
η+f0
ρ+ω
p+n
Δ,Y
b

(Photon) Reheating

When the temperature drops below the mass of a particle species ($e^{\pm}$-pairs), the species disappears (and if still coupled) transferring in an adiabatically expanding Universe its entropy into the remaining thermally coupled particles.

In the standard model of neutrino freeze-out, the CNB and CMB temperatures differ by ($e^{\pm}$-pairs) reheating factor

$$R_\nu \equiv T_\nu/T_\gamma = \left(\frac{4}{11}\right)^{1/3}. \tag{1}$$

This is the result of energy and entropy from $e^{\pm}$ annihilation going (nearly) into photons ONLY. Relativistic (massless) degrees of freedom impact speed of Universe expansion measurable in CMB fluctuation structure. This sets limit on any new dark radiation in the Universe.

Current status on CNB

- 'Effective' number of neutrinos defined comparing the relativistic energy density to the energy density of one SM neutrino flavor with standard $e^+e^- \to \gamma\gamma$ photon reheating ratio $R_\nu = (4/11)^{1/3}$ allowed for.

$$N_\nu \equiv N_{eff} \equiv \frac{\rho_r}{\frac{7}{120}\pi^2 \left(R_\nu T_\gamma\right)^4}. \quad (2)$$

- Planck satellite: $N_\nu = 3.36 \pm 0.34$ (CMB no priors) and $N_\nu = 3.62 \pm 0.25$ (CMB $+ H_0$) [1]. In latest release $\delta N_\nu \simeq 0.3 \pm 0.25$.

[1] *Planck Collaboration, Astron.Astrophys. 571 (2014) A16*

Is Understanding of Neutrino Freeze-out Accurate?

- The computed best value is $N_\nu = 3.046$ (some flow of $e^\pm$-pair into ν) [1]. Only drastic changes in neutrino properties and/or physical laws can change this value noticeably [2].
- Consistent $\delta N_\nu > 0$ – is there 'Darkness' content in the Universe? New relativistic particles in the early Universe modify N_ν fractionally, see e.g. [3].

[1] *G. Mangano et. al., Nucl. Phys. B* **729**, *221 (2005)*
[2] *J. Birrell, C. T. Yang and JR, Nucl. Phys. B* **890**, *481 (2014) [1406.1759 [nucl-th]]*
[3] *Steven Weinberg Phys. Rev. Lett.* **110**, *241301 (2013)*

Conservation of Entropy and Reheating Ratio

Once Darkness decouples from SM particles at a photon temperature of $T_{d,s}$, a difference in its temperature from that of photons will build up during subsequent reheating periods. Conservation of entropy leads to a temperature ratio at $T_\gamma < T_{d,s}$ of

$$R_s \equiv T_s/T_\gamma = \left(\frac{g_*^S(T_\gamma)}{g_*^S(T_{d,s})}\right)^{1/3}. \qquad (3)$$

This can be used to determine the present day reheating ratio as a function of decoupling temperature throughout the Universe history.

Degrees of Freedom

The temperature difference that develops during reheating is controlled by time dependence of the effective number of entropy degrees of freedom, g_*^S, defined by

$$S = \frac{2\pi^2}{45} g_*^S T_\gamma^3 a^3. \tag{4}$$

Darkness Candidates:

a) 'True' Goldstone bosons related to symmetry breaking in reorganization of QCD vacuum structure. My favorite candidate, theoretical details need work.

b) Super-WI neutrino partners. Connection to deconfinement not straightforward. Note that massive $m > \mathcal{O}(\text{eV})$ sterile ν not within 'Darkness' context. Mass must emerge after CMB decouples, $m < 0.25$ eV

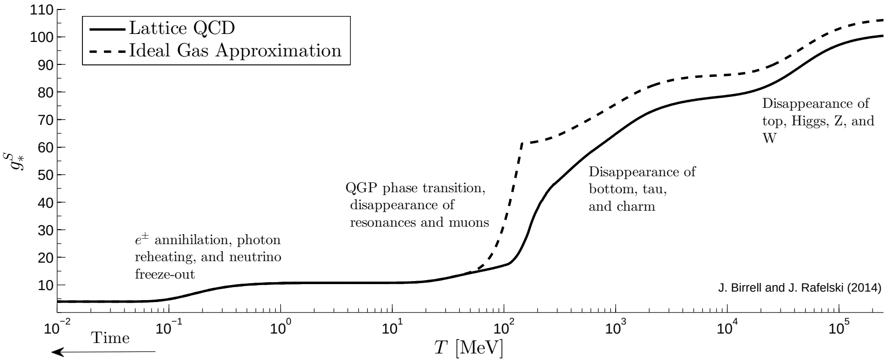


Figure: Ideal gas approximation is not valid during QGP phase transition and equation of state from lattice QCD must be used [1].

[1] *S. Borsanyi, Nucl. Phys. A904-905, 270c (2013)*

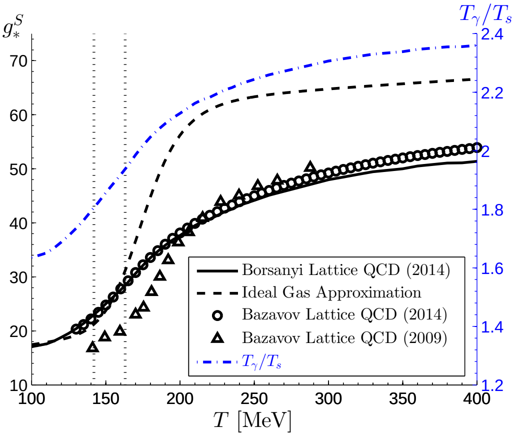


Figure: Left axis: Effective number of entropy-DoF. Right axis: Photon to Darkness temperature ratio, T_γ/T_s, as a function of Darkness decoupling temperature (dash-dotted line). The vertical dotted lines at $T = 142$ and 163 MeV delimit the QGP transformation region.

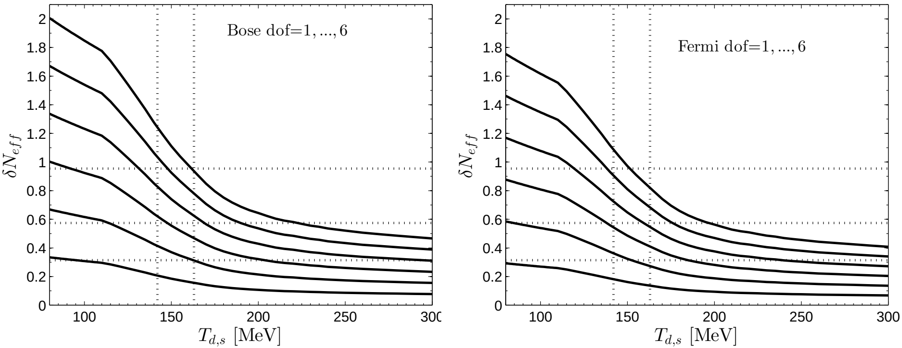


Figure: Left pane: Increase in δN_{eff} due to the effect of $1, \ldots, 6$ light Goldstone boson DoF ($g_s = 1, \ldots, 6$, bottom to top curves) as a function of freeze-out temperature $T_{d,s}$. Right pane: Increase in δN_{eff} due to the effect of $1, \ldots, 6$ light sterile fermion DoF ($g_s = 7/8 \times 1, \ldots, 7/8 \times 6$, bottom to top curves) as a function of freeze-out temperature $T_{d,s}$. The horizontal dotted lines: $\delta N_{\text{eff}} + 0.046 = 0.36, 0.62, 1$. Vertical dotted lines: $T_c = 142 - 163$ MeV.

Limits on Darkness Couplings:
SWI neutrinos

Cosmological setting: the lower bound for short range (S)uper WI style coupling required for SWI particles to remain in chemical equilibrium until the confining QGP transformation into regular matter at $T = \mathcal{O}(150\text{ MeV})$ is approximately

$$G_{\rm SWI}^{-1/2} \lesssim 9\,\text{TeV} \quad \text{compare} \quad G_{\rm WI}^{-1/2} = 300\text{ GeV} \tag{5}$$

This $10\,\text{TeV}$ energy scale for the coupling of SWI neutrinos seems reasonable and renders such particles within a range that can perturb experimental LHC laboratory data.

A set of three right handed SWI neutrino partners would make SM more symmetric comparing quarks with leptons.

Limits on Couplings:
Goldstone Boson limit in laboratory

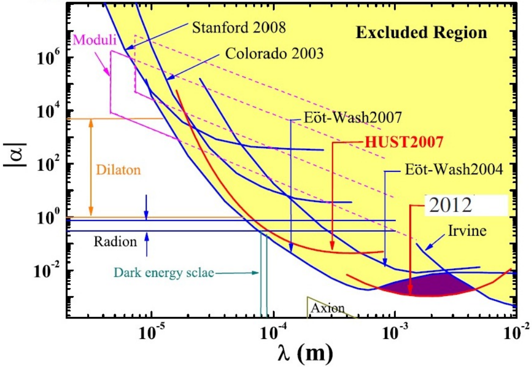
Laboratory setting: Chemical equilibrium abundance of Darkness is achieved in the short lifespan of QGP formed in laboratory heavy ion collisions if

$$G_{\mathrm{Darkness}}^{-1/2} \simeq 170\,\mathrm{MeV} \quad \text{compare} \quad G_{\mathrm{WI}}^{-1/2} = 300\ \mathrm{GeV}. \tag{6}$$

The appearance of a coupling on the order of the QCD scale is consistent with the intuition about the interaction strength that is required for particles to reach chemical equilibrium in laboratory QGP experiments. However, could such particles be excluded already by experiment?

Prior Searchers for Light Particles: a) 5th Force [1]

$rV = -Gm_1m_2(1+\alpha e^{r/\lambda})$ where $\lambda = 200\mu\mathrm{meV}/m$. For scale of mass $m > 20$ meV, $\lambda < 10^{-5}$ meter, 5th force experiments loose sensitivity but maybe not fast enough.



[1] *Shan-Qing Yang, Bi-Fu Zhan, Qing-Lan Wang, Cheng-Gang Shao, Liang-Cheng Tu, Wen-Hai Tan, and Jun Luo, Phys. Rev. Lett. 108, 081101 (2012)*

Prior Searchers for Light Particles: b) Kaon Decay

The Darkness with vacuum quantum number 0^+ can attach to all allowed reactions.

Prior experiment relies on observing the ‘dark’ particle decay, typically into $e^{\pm}$-pair $[1]$, our Darkness could not be observed that way.

Check of other past and proposed experiments did not reveal any directly relevant work for $m > 10$meV.

$[1]$ *N. J. Baker [et al]: Phys. Rev. Lett. 59, 2832 (1987)*

HOWEVER: Activation of QCD Scale Interactions by T

- For QCD-scale coupling to be consistent with the present day invisibility of Darkness, their interaction with other particles must only turn on in the domain where the vacuum is modified at finite temperature.
  Compare an analogous enhancement of anomalous baryogenesis at GUT scale temperatures [1].
- IF so: Without contradiction to what we have measured and despite QCD scale interaction, Darkness associated with the deconfined phase transition could be produced abundantly in laboratory relativistic heavy ion experiments.

[1] *V.A. Kuzmin, V.A. Rubakov, and M.E. Shaposhnikov, Phys. Lett. B155, 36 (1985)*

QGP activation: Missing Energy in RHI Collisions

- Breakup: Counting degrees of freedom and presuming Darkness equilibration before hadronization, approximately $12 \pm 8\%$ of all entropy content of the QGP is in Darkness.
- Continuous emission: Darkness stops interacting at the QGP surface – escapes freely during the entire lifespan of the QGP. This Dark-radiation loss proportionally largest for long-lived QGP $\rightarrow$ Does energy in/out balance in large AA collision systems beyond threshold of QGP formation?
- Experiment: A systematic exploration of the energy balance as function of $\sqrt{s}$ and A at energies near to QGP formation threshold: = NA61 experiment..

QGP Phase Transition Accentuated

- We recall that lattice-QCD results show a gradual transformation of the QGP into hadrons consistent with the absence of a phase transition.
- However, Darkness as above introduced contributes to the pressure internal to QGP, yet not in the external region – free streaming. This should sharpen the QGP phase boundary surface.
- This impacts model of QGP flow and formation azimuthal asphericity [1,2] (particle v_2). Darkness thus has indirect, dynamical effect on the flow of QCD matter.

[1] *Y.J. Ollitrault, Phys.Rev. D46, 229 (1992)*
[2] *S. Voloshin and Y. Zhang, Z.Phys. C70, 665 (1996)*

Summary

- We showed quantitatively how freeze-out of a reasonable number of Bose or fermi DoF at T_c during the QGP phase transition in the Universe leads to δN_ν in the range compatible with Planck.
- The existence of such Dark QCD related particles should lead to observable effects in heavy ion collisions: search for missing energy in connection to dynamics of hadronization near to phase boundary as function of $\sqrt{s}$ with energy imbalance increasing with A.