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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.

What has CMB to do with QGP?

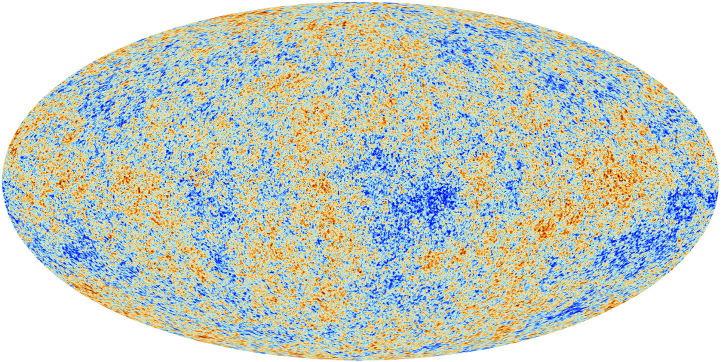


Figure: Photons freeze-out around 0.25 eV and today they make up the $T_\gamma = 0.235$ meV (2.7° K) Cosmic Microwave Background (CMB). The CMB is one of the anchors of observational cosmology

Image: ESA and the Planck Collaboration

Outline of the talk

- CMB connects with Cosmic Neutrino Background (CNB)
- Cosmic Neutrino Freeze-out forms the Background CNB
- Dynamics of Universe evolution checks CNB δN_ν, a bridge to Quark Universe

Impact of 'Darkness'[1] on N_ν

- Show particle Freeze-out generates δN_ν at QGP Phase Transition
- Required coupling for new particles

Laboratory Signature of Darkness

[1] Undiscovered and 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 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.

(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 particles.

In the standard model of neutrino freeze-out, the relic neutrino background and CMB temperatures differ by a 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 into photons ONLY. Relativistic (massless) degrees of freedom impact s speed of Universe expansion measurable in CMB fluctuation structure.

How one uses CMB to check 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.

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

- Planck satellite: $N_\nu = 3.36 \pm 0.34$ (CMB no priors) and $N_\nu = 3.62 \pm 0.25$ (CMB $+ H_0$) [1].
  $\delta N_\nu = 0.62 \pm 0.25$ motivates this talk.

[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].
- δN_ν also probes 'Darkness' particle content in the Universe: new relativistic particles in the early Universe modify N_ν, 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)*

Fractional δN_ν from New Particles

By definition of N_ν one naively expects:

- Each relativistic 4-component fermion: $\delta N_\nu = 1/2$
- Each relativistic boson DoF contributes $\delta N_\nu = 4/7$

Non-naive δN_ν: **Reheating:** When a particle species freezes

out and then the Universe reheats due to disappearance of other particles, the earlier frozen-out species retains a lower temperature compared to photons and hence contributes a smaller amount to δN_ν.

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

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

For ideal Fermi and Bose gases

$$g_*^S = \sum_{i=\text{bosons}} g_i \left(\frac{T_i}{T_\gamma}\right)^3 f_i^- + \frac{7}{8} \sum_{i=\text{fermions}} g_i \left(\frac{T_i}{T_\gamma}\right)^3 f_i^+. \tag{4}$$

g_i are the degeneracies, $f_i^\pm$ are functions varying valued between 0 and 1 that turn off the various species as the temperature drops below their mass.

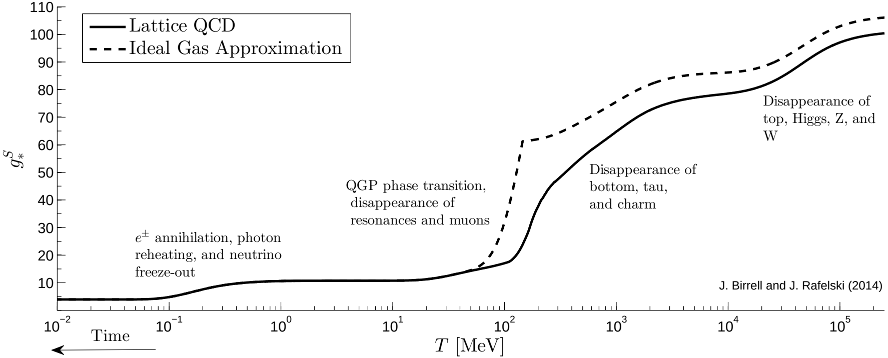


Figure: Ideal gas approximation is not valid during QGP phase transition and equation of state from lattice QCD must be used [1]. At and above 300 MeV non-rigorous matching [2] with perturbation calculations may impact result.

[1] *S. Borsanyi, Nucl. Phys. A904-905, 270c (2013)*
[2] *Mike Strickland (private communication of results and review of thermal SM).*

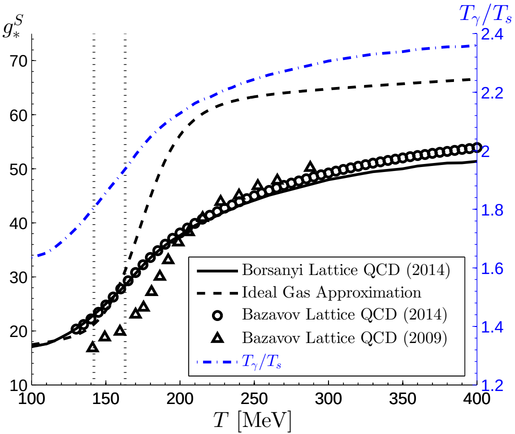


Figure: Left axis: Effective number of entropy-DoF. Right axis: Photon to Darkness temperature ratio, T_γ/T_s, as a function of Darkness decoupling temperature (dash-dotted line). The vertical dotted lines at $T = 142$ and 163 MeV delimit the QGP transformation region.

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

$$R_s \equiv T_s/T_\gamma = \left(\frac{g_*^S(T_\gamma)}{g_*^S(T_{d,s})}\right)^{1/3}. \tag{5}$$

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

Reheating and Particle Disappearance History

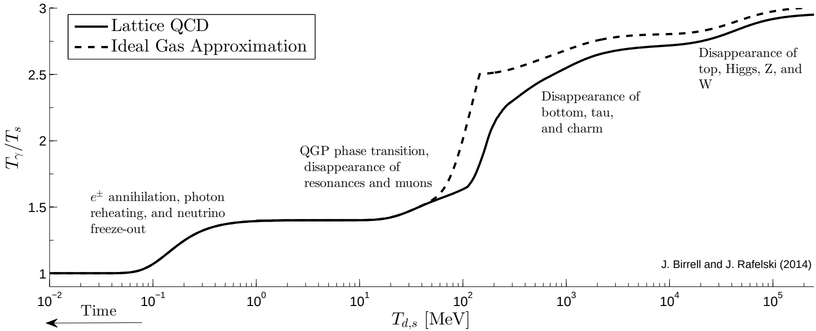


Figure: Cube of the present day ratio of photon temperature to the temperature of a particle species that decoupled at $T_{d,s}$. The reheating ratio reflects the disappearance of degrees of freedom from the Universe. At and above 300 MeV non-rigorous matching with perturbation calculations may impact result.

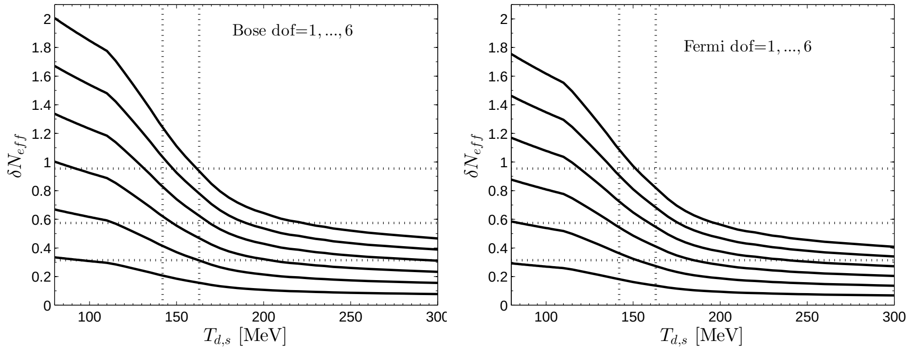


Figure: Left pane: Increase in $\delta N_{\rm eff}$ due to the effect of $1, \ldots, 6$ light sterile boson DoF ($g_s = 1, \ldots, 6$, bottom to top curves) as a function of freeze-out temperature $T_{d,s}$. Right pane: Increase in $\delta N_{\rm eff}$ due to the effect of $1, \ldots, 6$ light sterile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

How Many Dark Particles if Decoupling Related to Deconfinement? The best N_{eff} constraint suggests a multiplicity of 3 ± 2 Darkness at QGP hadronization, at which point there are about $g_*^S = 25$ strong interaction (entropy) degrees of freedom. As $25 \to 0$ we find $3 \pm 2 \to 0.6 \pm 0.25$.

Candidates:

a) SWI neutrino partners. Connection to deconfinement not straightforward. Note that massive $m = \mathcal{O}(\text{eV})$ sterile ν not within 'Darkness' context.

b) 'True' Goldstone bosons related to symmetry breaking in reorganization of QCD vacuum structure. My favorite candidate, theoretical details need work. This connects this talk to this workshop.

Limits on Darkness Couplings: SWI neutrinos

In the 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

$$G_{\rm SWI}^{-1/2} \lesssim 9\,\text{TeV} \quad \text{compare} \quad G_{\rm WI}^{-1/2} = 300\text{ GeV} \tag{6}$$

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.

Such three right handed SWI neutrino partners would make SM more symmetric comparing quarks with leptons. An attractive circumstance fitting quantitatively the $\delta N_{\rm eff}$ input.

Limits on Couplings: Goldstone Boson limit if observable in laboratory

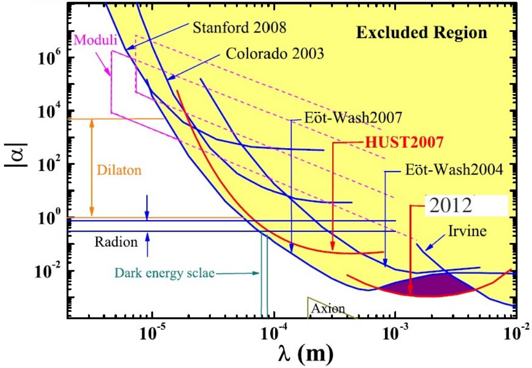
The other limit: Chemical equilibrium abundance of Darkness is achieved in the short lifespan of QGP formed in laboratory heavy ion collisions if

$$G_{\text{Darkness}}^{-1/2} \simeq 170\,\text{MeV}. \tag{7}$$

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. Conversely, QCD involvement in such new symmetry breaking ‘true’ Goldstones assures an experimental context in AA collisions. 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 $\lambda = 200\mu\text{meV}/m$. 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 $m > 10 meV$. HOWEVER

K$^\pm \to \pi^\pm + D$ process goes via virtual W$^\pm$ into off-mass shell $\pi^\pm$. Darkness puts pion to mass shell. Computed rate will probably exclude Darkness if effective QCD strength coupling with pions without activation.

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

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

- Counting degrees of freedom and presuming Darkness equilibration before hadronization, approximately $12 \pm 8\%$ of all entropy content of the QGP is in Darkness.
- Since Darkness stops interacting at the QGP surface, it escapes freely during the entire lifespan of the QGP. The dynamic effect increases energy loss considerably for large AA collision systems.
- HOW MEASURED: A systematic exploration of the thermal energy in the QGP fireball is presented in tables 8 and 9 in Ref.[1]: shows missing energy of the here estimated magnitude, 75% of the energy per baryon is found in the visible QGP reaction products.
- However: we did not consider the kinetic energy from collective matter flow, small when full stopping and little radial flow at the lowest energies at presumed QGP formation onset.

[1] *J. Letessier and J. Rafelski, Eur.Phys.J. A35, 221 (2008)*

QGP Phase Boundary: 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, Goldstone Darkness as above introduced contributes to the pressure internal to QGP, scattering from QGP partons, yet not in the external region. This creates a discontinuity at the QGP surface.
- Darkness could also be observed through its indirect, dynamical effect on the flow of matter, helping for example understand the dynamical azimuthal asphericity [1,2] (particle v_2),

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

Summary

- The freeze-out of relativistic 1–3 SWI neutrinos, and/or phase transition Goldstone bosons in the early Universe near QGP hadronization where MANY DoF disappear contributes fractionally to δN_ν.
- We showed this quantitatively: freeze-out of a reasonable number of bose or fermi DoF at T_c during the QGP phase transition leads to δN_ν in the range seen by Planck.
- This also suggests a connection between QGP phase transitions in early Universe and δN_ν.
- The existence of such Dark QCD related particles should lead to observable effects in heavy ion collisions: missing energy, dynamics of hadronization were mentioned.