BSM candidates for late decaying particles

Probing fundamental physics with CMB spectral distortions

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“The universe is the poor man’s accelerator . . . all we have to do is collect the experimental data and interpret them properly”

Yakov Zel’’dovich

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Time scales for photon interactions

- Today \( t_0 \)
  - Life on earth
  - Solar system
  - Quasars

Galaxy formation
  - Epoch of gravitational collapse

Recombination
  - Hubble radiation decouples (CMB)

Matter domination
  - Onset of gravitational instability

Nucleosynthesis
  - Light elements created - D, He, Li

Quark-hadron transition
  - Hadrons form - protons & neutrons

Electroweak phase transition
  - Electromagnetic & weak nuclear forces become differentiated:
  - \( SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \times U(1) \)

Grand unification transition
  - \( G \rightarrow H \rightarrow SU(3) \times SU(2) \times U(1) \)
  - Inflation, baryogenesis, monopoles, cosmic strings, etc.

The Planck epoch
  - The quantum gravity barrier
Far Infra Red Absolute Spectrophotometer (differential polarizing Michelson interferometer) compares sky temperature with internal calibrated blackbody (John Mather)

→ Zero output when the two inputs are equal
Observations at low frequencies are sensitive to possible spectral distortions.
The thermalisation of the spectrum proceeds through scattering of hot electrons (at temperature $T_e$) on the CMB photons, described by the:

Kompaneets (1957, Sov. Phys. JETP, 4, 730) equation:

$$\frac{\partial n}{\partial y} = x^{-2} \frac{\partial}{\partial x} \left[ x^4 \left( n + n^2 + \frac{\partial n}{\partial x} \right) \right]$$

where $n$ is the number of photons per mode ($n = 1/(e^x - 1)$ for a blackbody), $x = h\nu/kT_e$, and the Kompaneets $y$ is defined by

$$dy = \frac{kT_e}{m_e c^2 n_e \sigma_T c dt}.$$ 

Total photon number conserved:

$$\frac{\partial N}{\partial y} \propto \int x^2 \frac{\partial n}{\partial y} dx$$

$$= \int \frac{\partial}{\partial x} \left[ x^4 \left( n + n^2 + \frac{\partial n}{\partial x} \right) \right] dx$$

$$= 0$$

Diffusion in momentum space, with the frequency increasing on average per collision (for $h\nu \ll kT_e$) by $\Delta \nu/\nu \sim T_e/m_e$ due to the Doppler effect.
The stationary solutions $\partial n/\partial y = 0$ are general Bose-Einstein thermal distributions:

$$n = 1/(\exp(x + \mu) - 1)$$

$$N \propto \int \frac{x^2 dx}{\exp(x + \mu) - 1}$$

$$= \sum_{k=1}^{\infty} e^{-k\mu} \int x^2 e^{-kx} dx$$

$$= 2 \sum_{k=1}^{\infty} \frac{e^{-k\mu}}{k^3}$$

$$= 2 (\zeta(3) - \mu \zeta(2) + \ldots)$$

A similar calculation for the energy density shows that

$$U \propto 6 (\zeta(4) - \mu \zeta(3) + \ldots).$$

For $N = \text{const}$, need $\Delta T/T = \mu \zeta(2)/(3\zeta(3))$.

Therefore, the energy density change at constant $N$ is

$$\frac{\Delta U}{U} = \left( \frac{4\zeta(2)}{3\zeta(3)} - \frac{\zeta(3)}{\zeta(4)} \right) \mu = 0.714 \mu.$$

FIRAS limit $|\mu| < 9 \times 10^{-5}$ implies

$$\Delta U/U < 6 \times 10^{-5}$$
To reduce $\mu \to 0$ requires the creation of photons i.e. radiative processes.

Bremsstrahlung

Double Compton scattering

Illarianov & Sunyaev, Sov.Astron.\textbf{18}:691,1975;
Since \((1 + z) \partial y / \partial z \propto \Omega_B h^2 (1 + z)^2\), the overall rate for eliminating a \(\mu\) distortion scales like \(\Omega_B h^2 (1 + z)^{5/2}\) per Hubble time. A proper consideration (Burigana et al. 1991, ApJ, 379, 1-5) of this interaction of the photon creation process with the Kompaneets equation shows that the redshift from which \(1/e\) of an initial distortion can survive is

\[
z_{\text{th}} = \frac{4.24 \times 10^5}{[\Omega_B h^2]^{0.4}}
\]

which is \(z_{\text{th}} = 1.9 \times 10^6\) for \(\Omega_B h^2 = 0.0224\).

**Caveat:** If the injection of EM energy is from a particle which **matter-dominated** the Hubble expansion rate before decaying then the thermalisation redshift (for a very large energy release) increases to: \(\sim 3.9 \times 10^6 \left[\Omega_B h^2\right]^{1/3}\)

Sarkar & Cooper, PL 184B: 347,1984
The **Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model**, viewed as an **effective field theory**, provides an exact description of all microphysics (up to some high energy cut-off $M$).

\[
L_{\text{eff}} = F^2 + \bar{\Psi} D\Psi + \bar{\Psi} \Psi \Phi + (D\Phi)^2 + V(\Phi) + \frac{\bar{\Psi} \Psi \Phi \Phi}{M} + \frac{\bar{\Psi} \Psi \Psi \Psi}{M^2} + \ldots
\]

Higgs mass divergence

\[
m_H^2 \approx \frac{g_i^2}{16\pi^2} \int_0^M dk^2 = \frac{g_i^2}{16\pi^2} M^2
\]

Possible solution for Higgs mass divergence $\Rightarrow$ ‘softly broken’ supersymmetry at $\sim 1\text{TeV}$

The effect of new physics beyond the SM (neutrino mass, nucleon decay, FCNC) $\Rightarrow$ **non-renormalisable operators** suppressed by $M^n$ ... which ‘decouple’ as $M \rightarrow M_P$

But as $M$ is raised, the effects of the super-renormalisable operators are exacerbated.

The **lightest** supersymmetric state – the neutralino $\chi$ – is a candidate for **dark matter** (similarly in other extensions of the SM, e.g. **new dimensions** $\rightarrow$ Kaluza-Klein states).

But if the Higgs is **composite** (as in **technicolour** models of $SU(2)_L \times U(1)_Y$ breaking) then there is no need for supersymmetry and the lightest TC state can be dark matter.

If the symmetry stabilising the new particles (viz. $R$-parity in supersymmetry) is **not** exact, then such particles can decay with **cosmologically interesting lifetimes**.
The lightest states in the SM are *stable* because of conserved quantum numbers corresponding to gauged \((local)\) symmetries *viz.* electric charge and colour.

Neutrinos quantum-mechanically mix between different flavours, hence being neutral, heavier mass eigenstates can *decay* into lighter ones ... although this is strongly *suppressed* by chirality and the unitarity of the mixing matrix (GIM mechanism).


The lifetime is *longer* than the age of the universe so such decays occur too late for the decay photons to be (partially) thermalized and create \(\mu\) or \(\gamma\) spectral distortions.
Such very long-lived decaying particles would increase the ionisation fraction of the intergalactic medium and *broaden* the ‘last scattering surface’ of the CMB.

This would damp the acoustic peaks in the power spectrum of CMB fluctuations – as was noted first for a model of decaying dark matter (~27 eV mass neutrinos).

**Cosmic microwave background anisotropy in the decaying neutrino cosmology**

This result is easily generalised to *any* source of ionising photons (E >13.6 eV) *e.g.* generated in the annihilation of dark matter particles (and resulting radiation cascades), and can be strengthened using polarisation (Chen & Kamionkowski, PRD70:023502,2004; Padmanabhan & Finkbeiner, PRD72:023508,2005; Slatyer, PRD93:023527,2016)
Now that the CMB power spectrum is known to $O(\%)$ accuracy, *Planck* data sets a strong limit, *disfavouring* dark matter interpretations of the PAMELA/AMS-02 positron anomaly.

This complements other observational constraints, however the sensitivity is *not* sufficient to constrain annihilations at the rate expected for *thermal relic* dark matter.
If right-handed ("singlet") neutrinos are added to the SM, then the FCNC decay into invisible neutrinos can be much faster (avoiding GIM suppression), however the rate of such decays can be related to the concomitant radiative decay width:

\[ \Gamma(x \rightarrow \nu\gamma)/\Gamma(x \rightarrow \nu\nu\nu) = \frac{27\alpha}{8\pi} = \frac{1}{128} \]

... so invisible decays will always be accompanied by visible decays which will affect the CMB and X-ray backgrounds (Barger, Phillips & Sarkar, PL B352:365,1995)
Such sterile (right-handed) neutrinos can in principle be the dark matter. These may mix with the left-handed ‘active’ neutrinos so would behave as super-weakly interacting particles with an effective coupling: \( \theta G_{\text{Fermi}} \)

\[
\theta^2_{e,\mu,\tau} \equiv \frac{|M_{\text{Dirac}}|^2}{|M_{\text{Majorana}}|^2} = \frac{M_{\text{active}}}{M_{\text{sterile}}} \approx 5 \times 10^{-5} \left( \frac{M_{\text{sterile}}}{\text{KeV}} \right)^{-1}
\]

So they will be created when active neutrinos scatter, at a rate

\( \propto \theta^2 \Gamma_{\text{active}} \)

Hence although they may never come into equilibrium, the relic abundance can be of order the dark matter for a mass of order KeV (Dodelson & Widrow, PRL 72:17,1994)
Much excitement about detection of possible decay line at \( \sim 3.5 \) keV!

7 keV ‘warm dark matter’, even if it exists, has too long a lifetime to create CMB distortions, however there may be other sterile neutrinos with MeV masses \( \Rightarrow \) shorter lifetimes which can e.g. solve the “Li problem” and be probed via their \( \mu \) distortions (Salvati et al, JCAP 08:022, 2016)
Can combine upper bounds on leptonic mixing from laboratory experiments with lower bounds inferred from BBN & CMB spectrum – to constrain new physics

Fig. 3. Upper limits on the leptonic mixing parameter $|U_{e3}|^2$ as a function of neutrino mass $m_{\nu_3}$, derived from: Searches for the decays (A) $\nu_3 \rightarrow e\nu$, $e\mu$, $e\tau$; (B) $\nu_3 \rightarrow e\nu$, $e\mu$, $e\tau$; (C) $\nu_3 \rightarrow e\nu$ [6] (uncorrected, see text); searches for secondary peaks in (D) $K \rightarrow e\nu$ [20]; (E) $\pi \rightarrow e\nu$ [18]. The region enclosed by curve (A) is excluded.

BEBC WA66 collab., PL 160B: 207,1985

Fig. 2. Experimental lower limits on the lifetime $\tau(\nu_3 \rightarrow e^-\nu_e)$ from: (a) TRIUMF [11], (b) CHARM [12] and on $\tau(\nu_3 \rightarrow \mu^-\nu_\mu)$ from (c) BEBC [13] and (c') KEK [13].

Cosmological upper limits from: (d) deuterium photofission, (e) primordial nucleosynthesis, (f) black-body background. There is no allowed region below (g), the MARK II [3] upper bound on $m_{\nu_3}$. The limits (a, d–f) apply to any heavy neutrino and rule out the mass range $1 \lesssim m_{\nu} \lesssim 50$ MeV.

Sarkar & Cooper, PL 184B: 347,1984

E.g. ruling out a MeV mass tau neutrino - similar strategy to be employed in the SHiP experiment.
Extensions of the Standard Model predict new *long-lived* particles, which would have been created in the early Universe, e.g. weak scale mass *gravitinos* in N=1 supergravity.

\[ \tilde{G} \rightarrow \gamma \tilde{\gamma} \]

Supersymmetry breaking origin (Hidden sector)  
Flavor-blind interactions  
MSSM (Visible sector)  

\[ \tau_{3/2} \approx 4 \times 10^5 \text{ s} \left( \frac{m_{3/2}}{1 \text{ TeV}} \right)^{-3} \]


→ \( \tilde{G} \) is the gauge field of *local* SUSY (=SUGRA) transformations  
→ superpartner of graviton, spin 3/2 Majorana field  
→ spontaneous SUSY breaking:  
  → super-Higgs mechanism:  
    goldstino becomes helicity ±1/2 components of \( \tilde{G} \)  
    depending on breaking: \( 10 \text{ eV} \lesssim m_{\tilde{G}} \lesssim 100 \text{ TeV} \)  
→ softly broken global SUSY (e.g. MSSM) + \( \tilde{G} \) interactions

Post-inflation generation by 2 \( \rightarrow 2 \) scatterings in thermal bath:  
\[ n_{3/2} \sim \frac{T_R}{M_P} \]

... these are dangerous relics as they can decay *after* BBN and CMB thermalisation.
The high energy photons trigger radiation cascades in the background plasma which can photodissociate the synthesized light elements and induce $\mu$ and $y$ distortions in the CMB spectrum $\Rightarrow$ \textbf{limit on the decaying gravitino abundance} (and correspondingly on the reheat temperature)


Most severe constraint from considering photofission of $^4\text{He} \rightarrow$ (much rarer) D, $^3\text{He}$

... can be generalised to any decaying particle (and updated with future limits on $\mu$ and $y$)
This implied a severe upper limit on the reheat temperature following inflation - which ruled out the possibility of GUT-scale baryogenesis ... and motivated attempts to create the observed baryon asymmetry at lower temperatures → leptogenesis (Ellis et al, Nucl.Phys. B373:399,1992)

If the gravitino is in fact the LSP, then the bound on the reheat temperature is relaxed ... but similar constraints then apply to the NLSP decays
FIRAS vastly improved the constraints on visibly decaying particles.

\[ \mu < 3.3 \times 10^{-4} \quad y < 2.5 \times 10^{-5} \]

\[ \Omega_b h^2 = 0.015 \]

Ellis et al., NP B373:399, 1992, Hu & Silk, PR D48:485, 1993
Reexamination of these arguments have lowered the reheat temperature bound (e.g. Kawasaki, Kohri, Moroi, Takaesu, PR D97:023502,2018) and the PIXIE sensitivity will probe to even lower temperature (Dimastrogiovanni, Chluba, Krauss, PRD94:023518,2016)
Another well-motivated metastable relic particle is a scalar singlet coupled to the SM via a (super-renormalisable)\textquoteleft Higgs portal\textquoteright: $\mathcal{L}_{H/S} = \mu^2 H^\dagger H - \lambda_H (H^\dagger H)^2 - \frac{m_S^2}{2} S^2 - ASH^\dagger H$

The mixing angle between the physical states is:

$$\theta = \frac{A u}{m_h^2 - m_S^2}$$

In the limit that $\theta \rightarrow 0$, the scalar is stable and could be the dark matter. In general it is metastable and its lifetime is severely constrained by both laboratory expts. and cosmology (produced through \textquoteleft freeze-in\textquoteright).

Especially stringent bounds on the mixing angle follow from consideration of the CMB spectral distortion constraints – future improvements by PIXIE (dashed lines) will probe extremely weakly coupled particles.

Fradette, Pospelov, Pradler, Ritz, PR D90:035022,2014; Fradette, Pospelov, PR D96:075033,2017
Summary

Spectral distortions of the CMB (complemented by its angular power spectrum) are a robust and sensitive probe of relic particle decays and annihilations, especially during the dark ages of the universe.

Recent detailed studies (see Chluba, Hamman, Patil, IJMP D24:1530023, 2015) provide a well-understood framework for confronting forthcoming observations (PIXIE ...) and revisiting old arguments.

Natural candidates for late decaying particles are those with only gravitational couplings (e.g. gravitinos) or suppressed mixings with the SM (e.g. sterile neutrinos, scalar singlets) ... which have been invoked to address shortcomings of the SM or account for new phenomena.

Improvements in the observational sensitivity to injection of EM energy which give rise to spectral distortions of the CMB will provide a valuable probe of new physics beyond the Standard Model.