BSM CANDIDATES FOR LATE DECAYING PARTICLES

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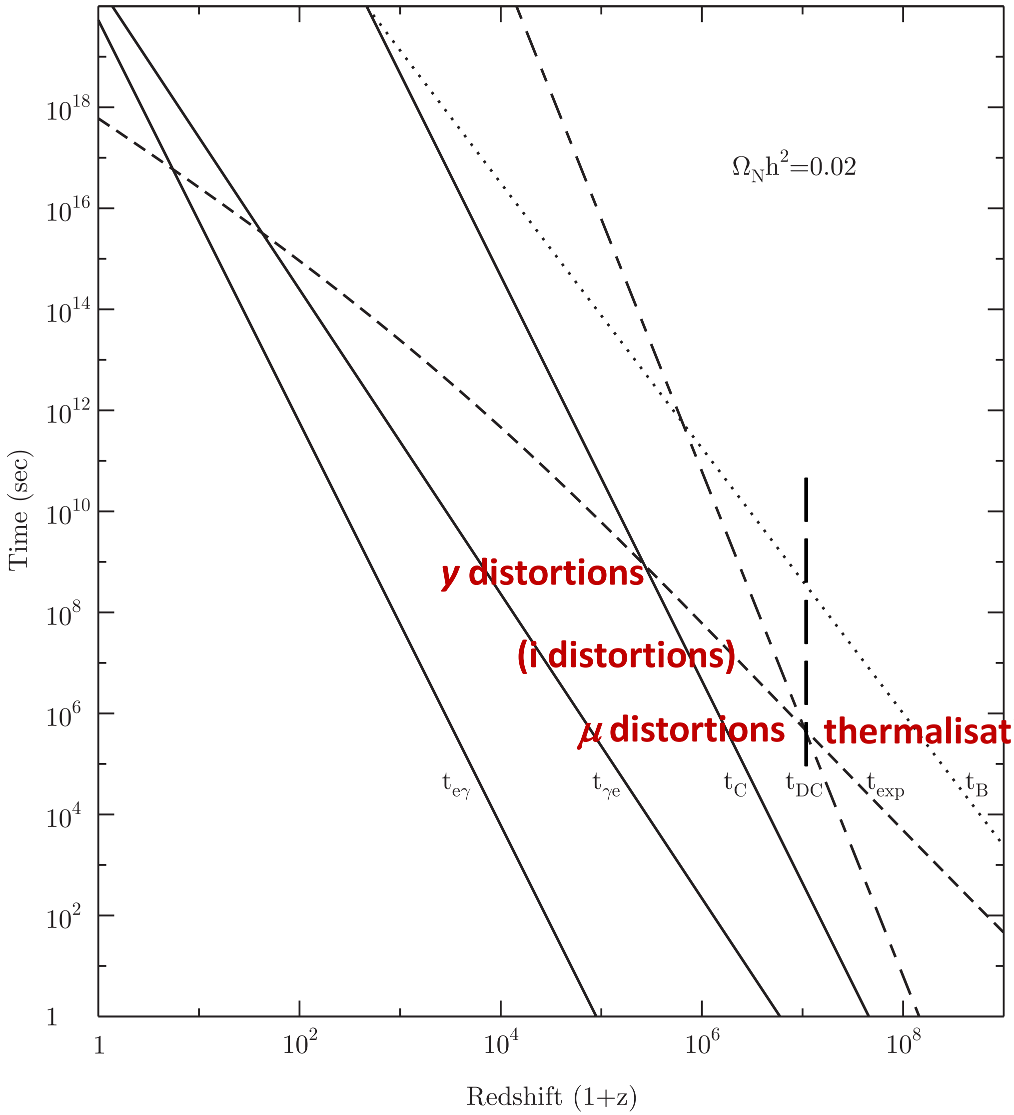
> *"The universe is the poor man's accelerator . . . all we have to do is collect the experimental data and interpret them properly"*

Yakob Zel'dovich

PROBING FUNDAMENTAL PHYSICS WITH CMB SPECTRAL DISTORTIONS

CERN GENEVA, 12-16 MARCH 2018

TIME SCALES FOR PHOTON INTERACTIONS

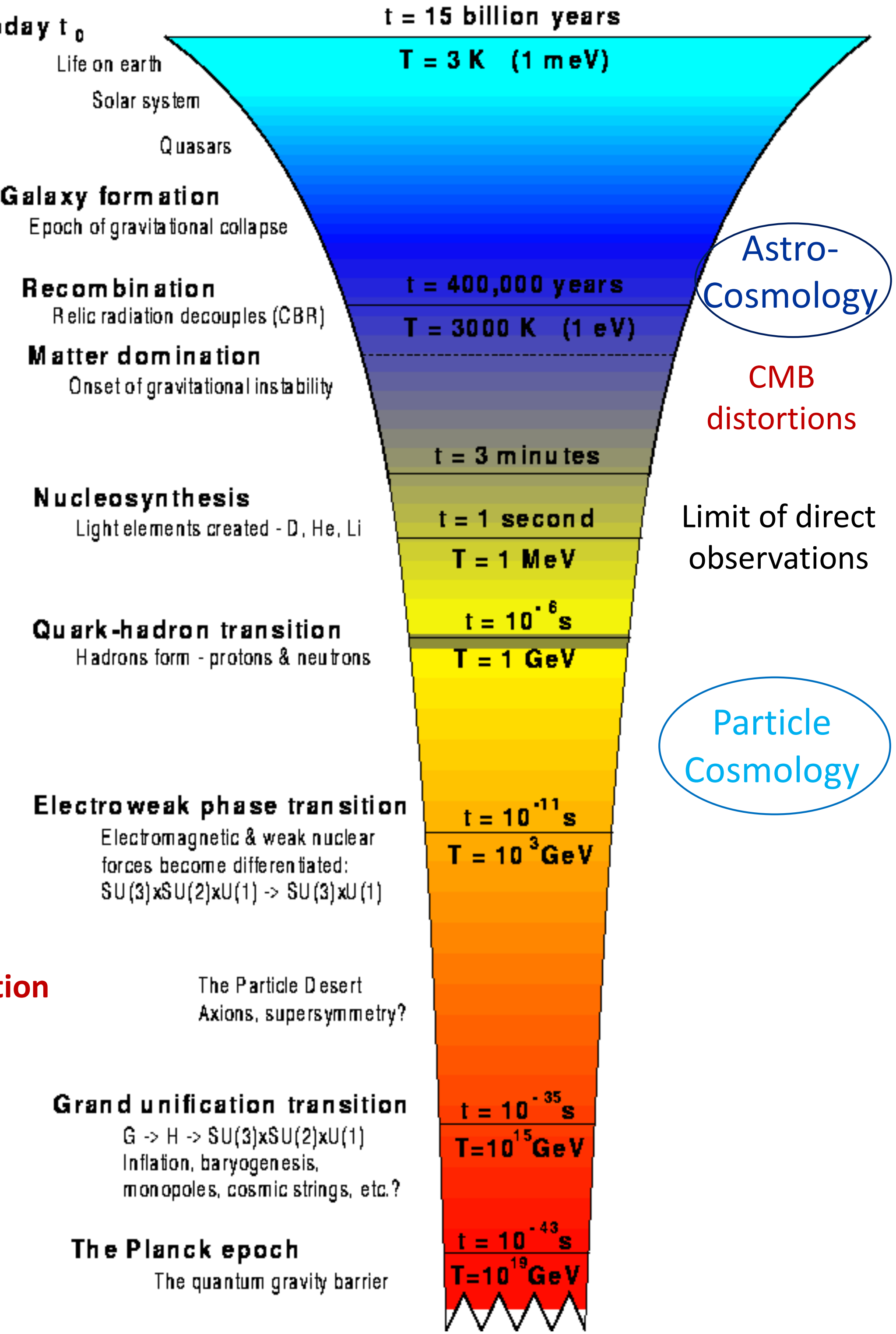


y distortions

(i distortions)

μ distortions

thermalisation



Today t$_0$ t = 15 billion years

T = 3 K (1 meV)

Life on earth

Solar system

Quasars

Galaxy formation

Epoch of gravitational collapse

Recombination t = 400,000 years

Relic radiation decouples (CBR) T = 3000 K (1 eV)

Matter domination

Onset of gravitational instability

t = 3 minutes

Nucleosynthesis

Light elements created - D, He, Li t = 1 second

T = 1 MeV

Quark-hadron transition t = 10^{-6}s

Hadrons form - protons & neutrons T = 1 GeV

Electroweak phase transition t = 10^{-11}s

Electromagnetic & weak nuclear forces become differentiated: SU(3)xSU(2)xU(1) -> SU(3)xU(1) T = 10^3GeV

The Particle Desert

Axions, supersymmetry?

Grand unification transition t = 10^{-35}s

G -> H -> SU(3)xSU(2)xU(1) T=10^{15}GeV

Inflation, baryogenesis, monopoles, cosmic strings, etc.?

The Planck epoch t = 10^{-43}s

The quantum gravity barrier T=10^{19}GeV

Astro-Cosmology

CMB distortions

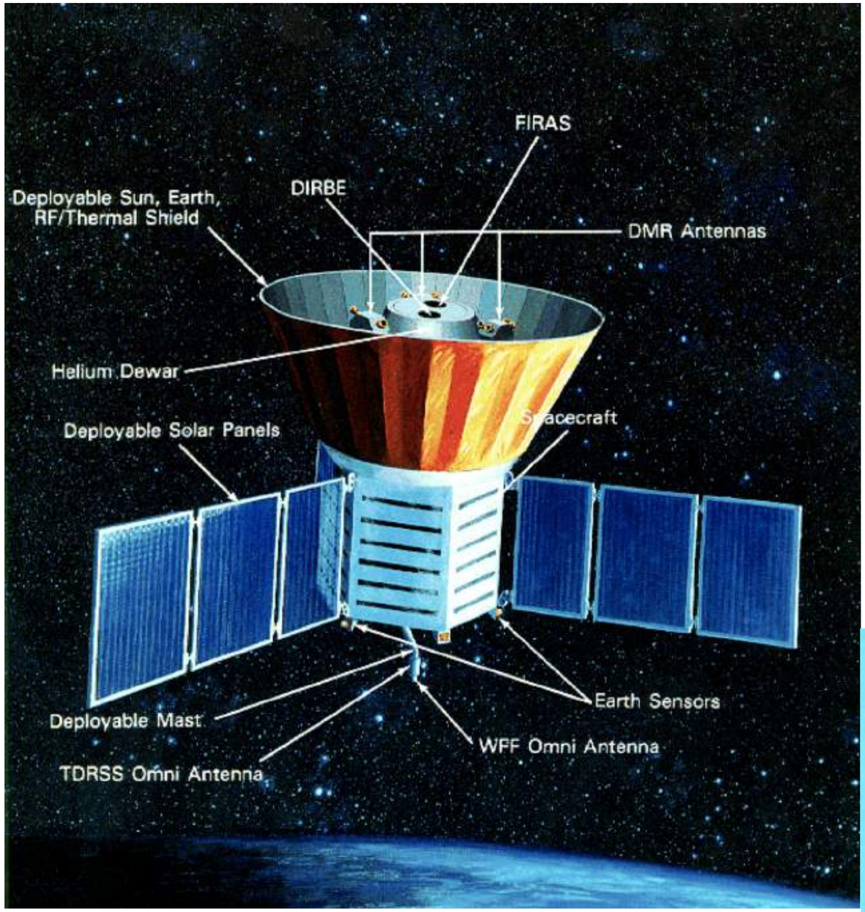
Limit of direct observations

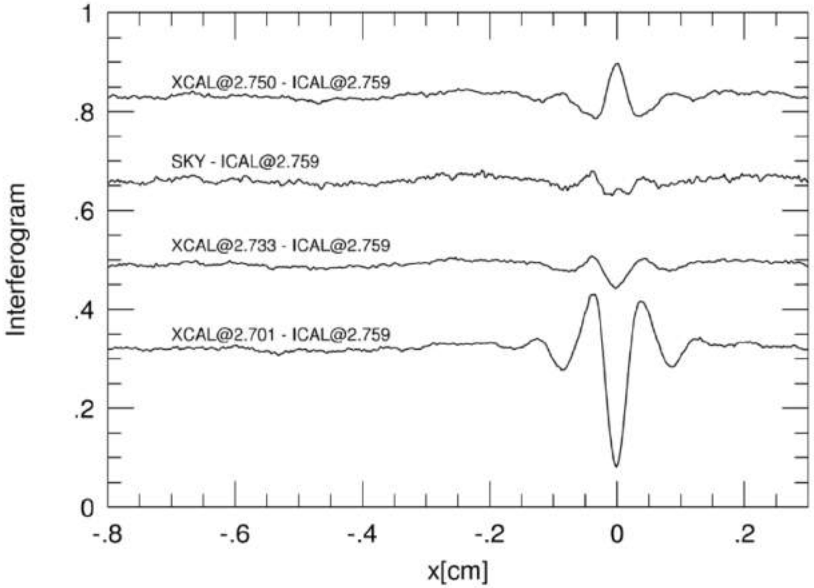
Particle Cosmology

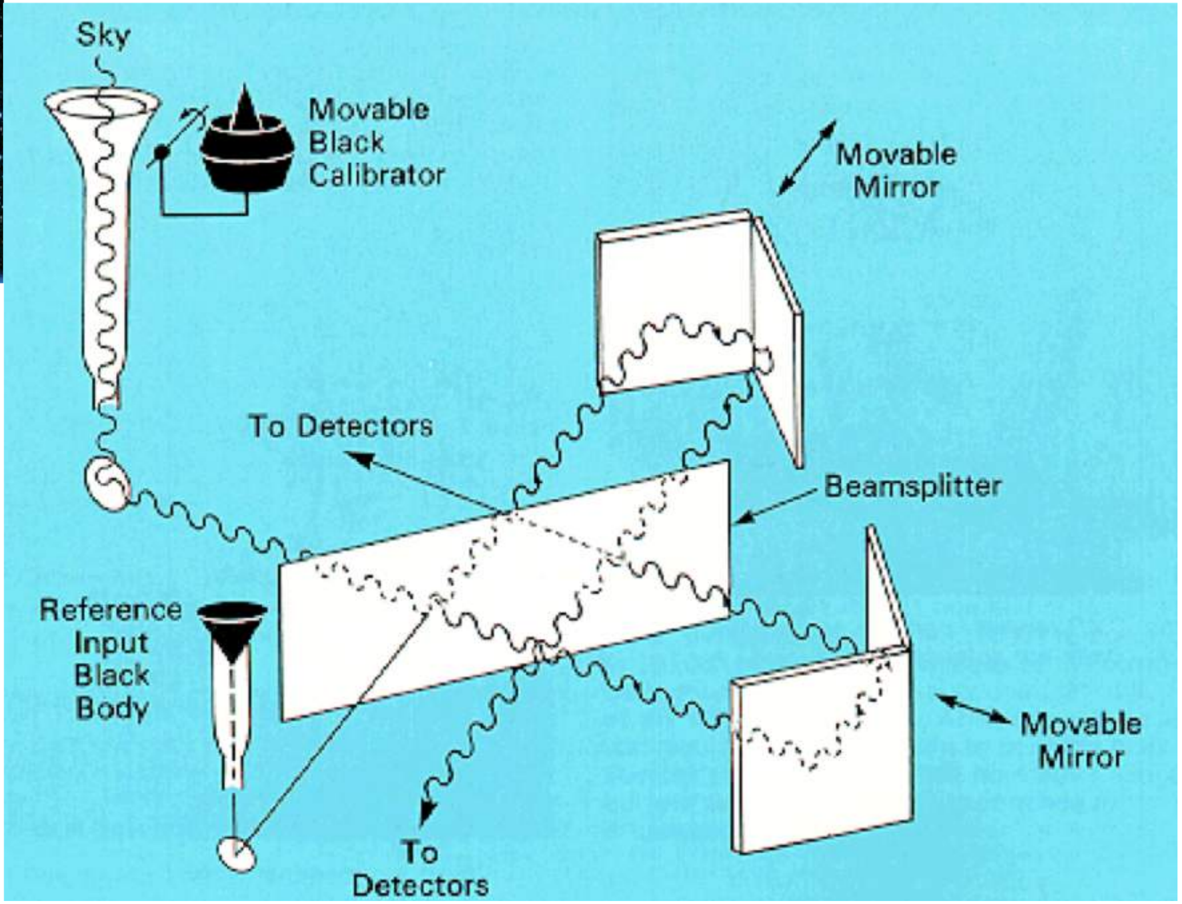
Far Infra Red Absolute Spectrophotometer
(differential polarizing Michelson interferometer)

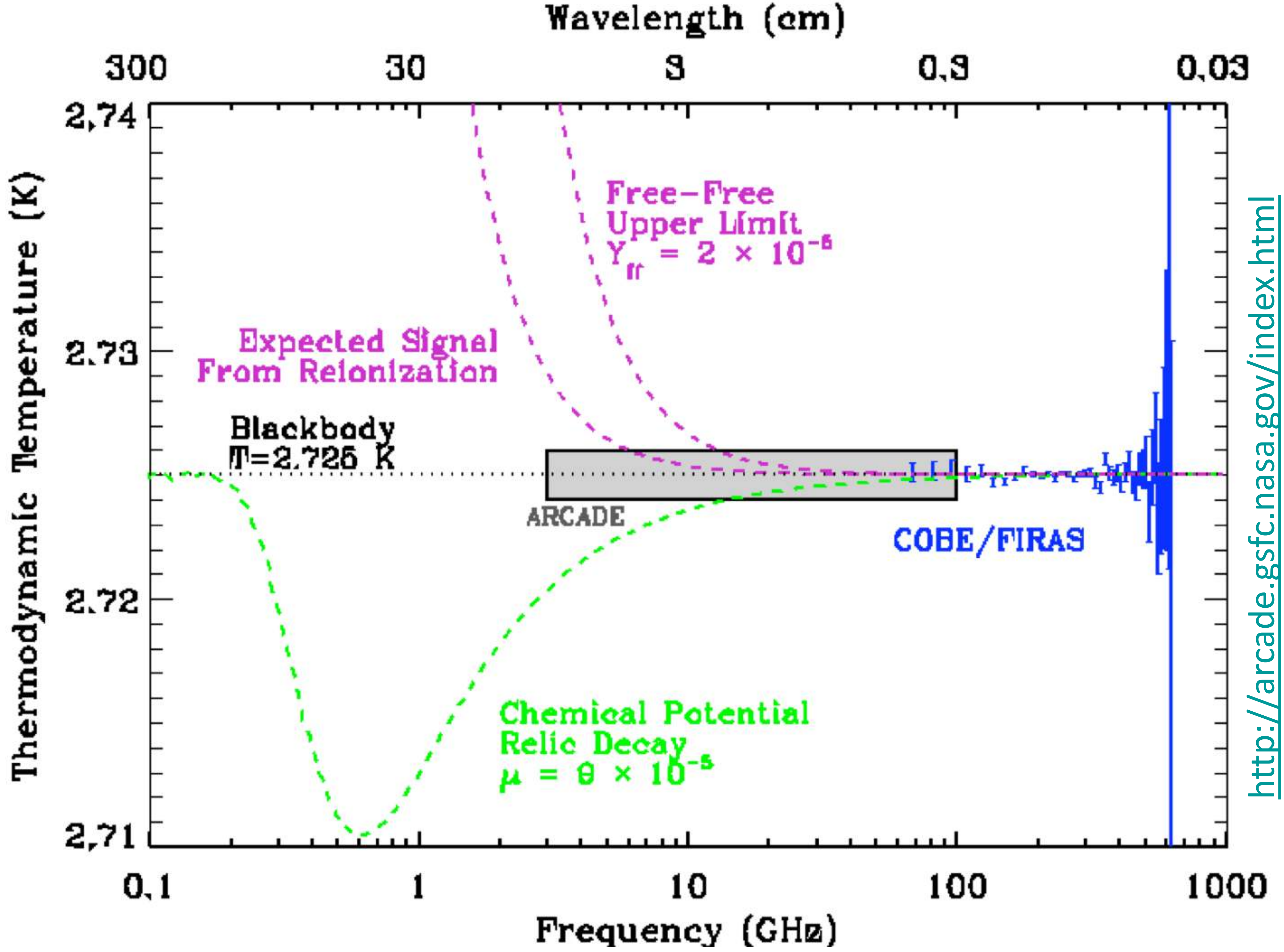
compares sky temperature with internal *calibrated* blackbody (John Mather)

→Zero output when the two inputs are equal





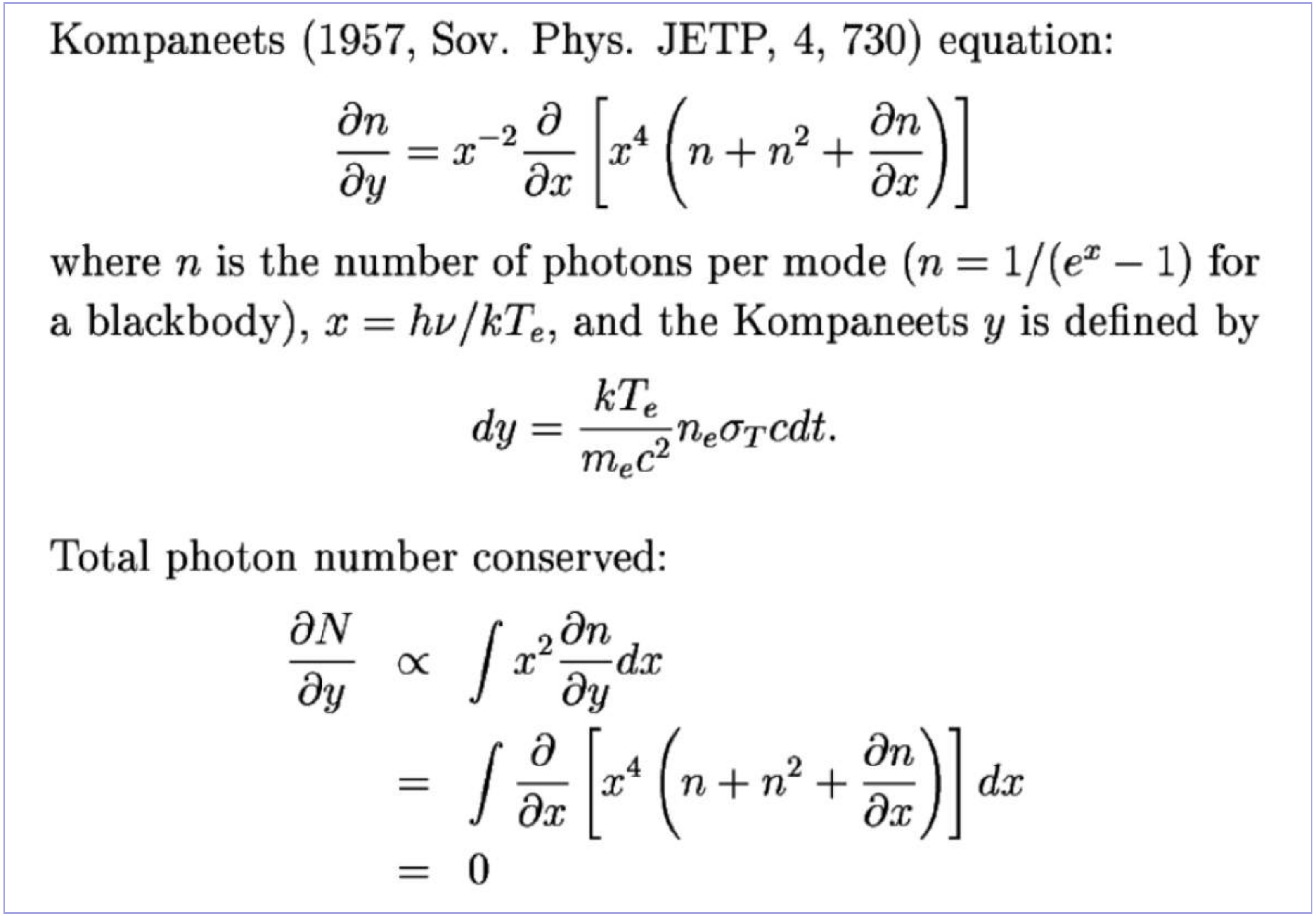




http://arcade.gsfc.nasa.gov/index.html

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:

$$\begin{aligned} \frac{\partial N}{\partial y} &\propto \int x^2 \frac{\partial n}{\partial y} dx \\ &= \int \frac{\partial}{\partial x} \left[x^4 \left(n + n^2 + \frac{\partial n}{\partial x} \right) \right] dx \\ &= 0 \end{aligned}$$

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:

$$\begin{aligned} n &= 1/(\exp(x+\mu)-1) \\ N &\propto \int \frac{x^2 dx}{\exp(x+\mu)-1} \\ &= \sum_{k=1}^{\infty} e^{-k\mu} \int x^2 e^{-kx} dx \\ &= 2\sum_{k=1}^{\infty} \frac{e^{-k\mu}}{k^3} \\ &= 2\left(\zeta(3) - \mu\zeta(2) + \ldots\right) \end{aligned}$$

A similar calculation for the energy density shows that

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

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

Therefore, the energy density change at constant N is

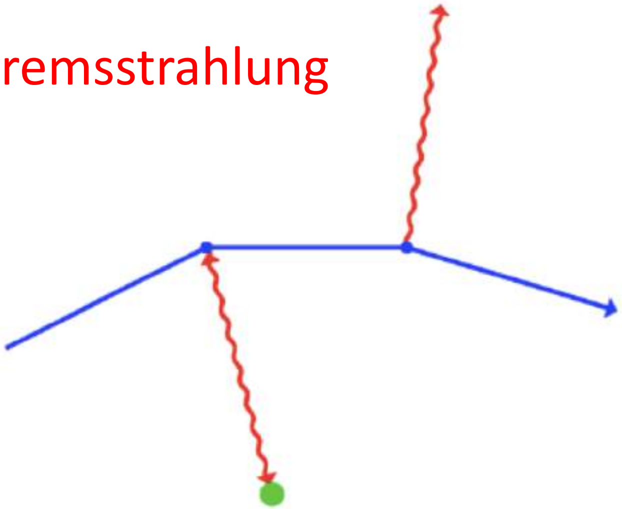
$$\frac{\Delta U}{U} = \left(\frac{4\zeta(2)}{3\zeta(3)} - \frac{\zeta(3)}{\zeta(4)}\right)\mu = 0.714\mu.$$

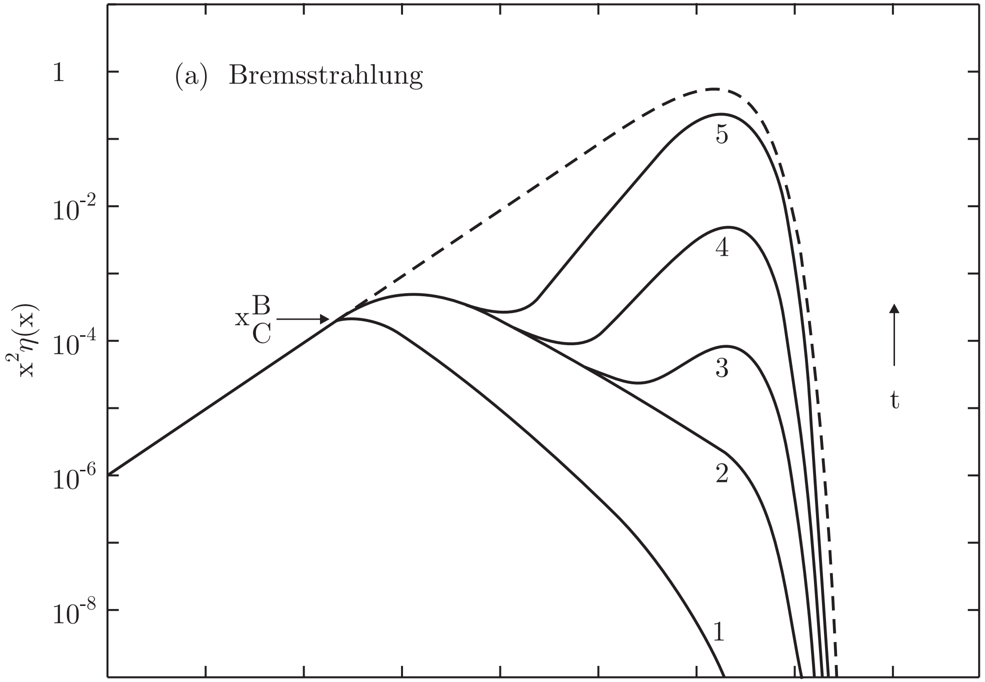
FIRAS limit $|\mu| < 9 \times 10^{-5}$ implies

$$\Delta U/U < 6 \times 10^{-5}$$

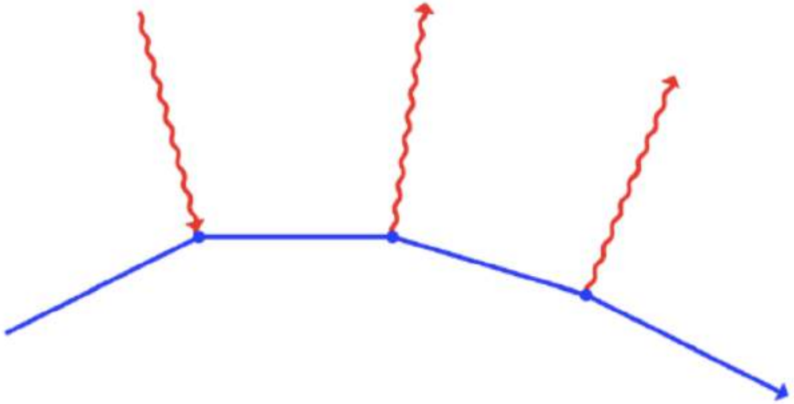
To reduce $\mu \rightarrow 0$ requires the creation of photons i.e. radiative processes

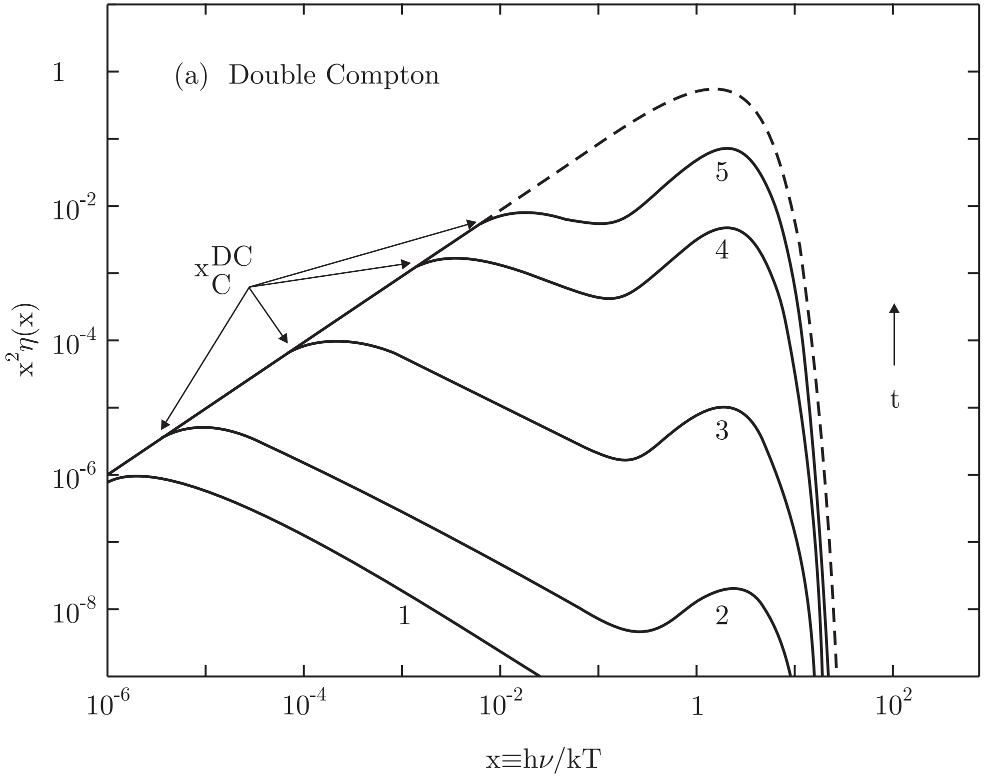
Bremsstrahlung





Double Compton scattering



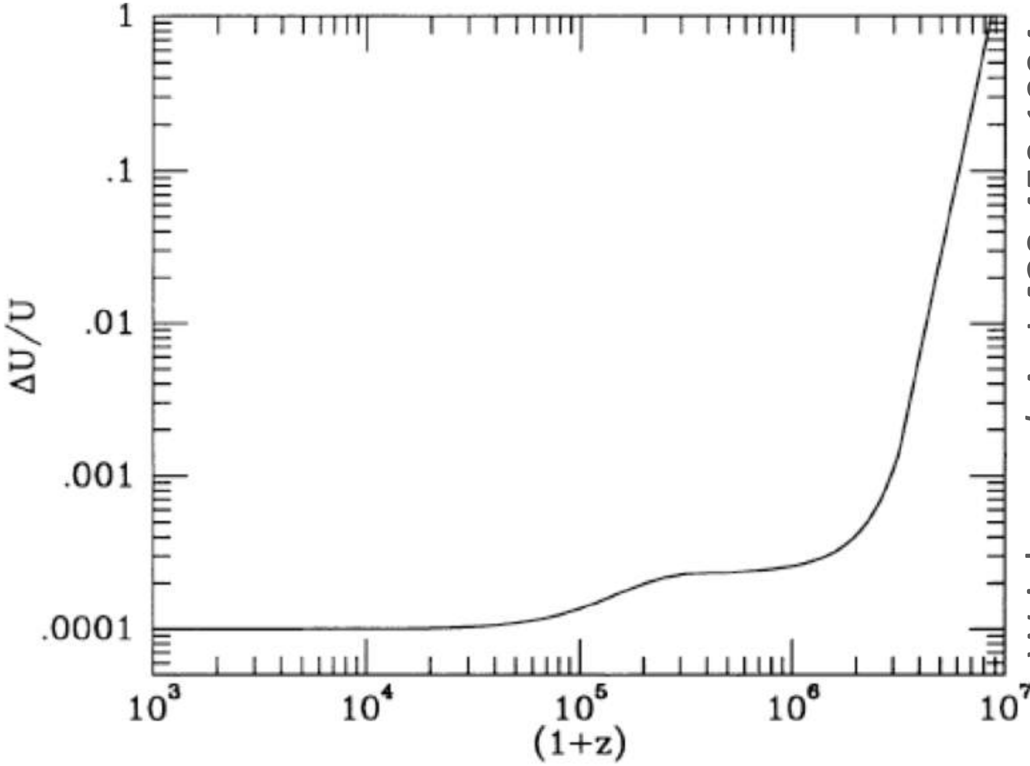


Sunyaev & Zeldovich, Astro.Sp.Sci.**7**:20,1970;
Illarianov & Sunyaev, Sov.Astron.**18**:691,1975;
Lightman, ApJ **244**:392,1981;
Danese & de Zotti, A&A **107**:39,1982

Since $(1+z)\partial y/\partial z \propto \Omega_B h^2 (1+z)^2$, the overall rate for eliminating a μ 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

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

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



Wright *et al*, ApJ **420**:450,1994

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: $\sim 3.9\text{x}10^6\,[\Omega_B h^2]^{1/3}$

Sarkar & Cooper, PL **184B**: 347,1984

The **Standard $SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$ Model**, viewed as an *effective* field theory, provides an exact description of all microphysics (up to some high energy cut-off M)

Higgs mass divergence

$$+M^4 + M^2\Phi^2 \quad m_H^2 \simeq \frac{h_t^2}{16\pi^2}\int_0^{M^2} \mathrm{d}k^2 = \frac{h_t^2}{16\pi^2}M^2$$

super-renormalisable

$$\mathcal{L}_{\text{eff}} = F^2 + \bar{\Psi}\,\not{D}\Psi + \bar{\Psi}\Psi\Phi + (D\Phi)^2 + V(\Phi)$$

renormalisable

$$\boxed{-\mu^2\phi^\dagger\phi + \tfrac{\lambda}{4}(\phi^\dagger\phi)^2, m_H^2 = \lambda v^2/2}$$

$$+\frac{\bar{\Psi}\Psi\Phi\Phi}{M} + \frac{\bar{\Psi}\Psi\bar{\Psi}\Psi}{M^2} + \ldots$$

non-renormalisable

The effect of new physics *beyond* the SM (**neutrino mass**, nucleon decay, FCNC) ⇒ ***non*-renormalisable operators** suppressed by M^n ... which 'decouple' as $M \to M_{\mathrm{P}}$

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

Possible solution for Higgs mass divergence ➛ 'softly broken' supersymmetry at ~1TeV

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

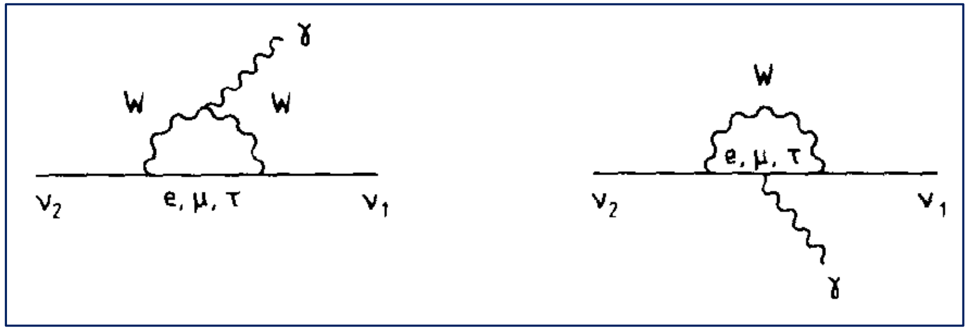
But if the Higgs is *composite* (as in **technicolour** models of $SU(2)_L$ x $U(1)_Y$ breaking) then there is no need for supersymmetry and the lightest TC state can be dark matter

If the symmetry stabilising the new particles (*viz. R*-parity in supersymmetry) is *not* exact, then such particles can decay with **cosmologically interesting lifetimes**

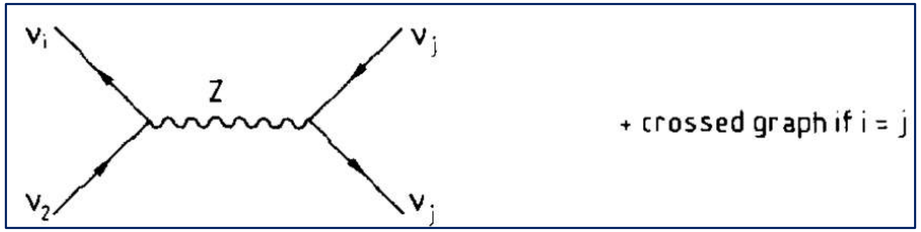
The lightest states in the SM are *stable* because of conserved quantum numbers corresponding to gauged (*local*) symmetries *viz.* electric charge and colour

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)

Petcov, Yad.Fiz.**25**:340,1977; Goldman & Stephenson, PR D**16**:2256,1977; Marciano & Sanda, PL **67**B:303,1977; Lee & Shrock, PR D**16**:1444,1977; Pal & Wolfenstein, PR D**25**:766,1982



Flavour-Changing Neutral Current - negligible rate in SM



$$\Gamma \approx \frac{\alpha}{2}\left[\frac{3G_F}{32\pi^2}\right]^2 \left[\frac{m_2{}^2-m_1{}^2}{m_2}\right]^3 (m_2{}^2+m_1{}^2)\left[\sum_a U_{1a}U_{2a}r_a\right]^2 \approx (10^{29}\ \mathrm{yr})^{-1}\left[\frac{m_2}{30\ \mathrm{eV}}\right]^5 (1-x^2)^3\,(1+x^2)(U_{1\tau}U_{2\tau})^2$$

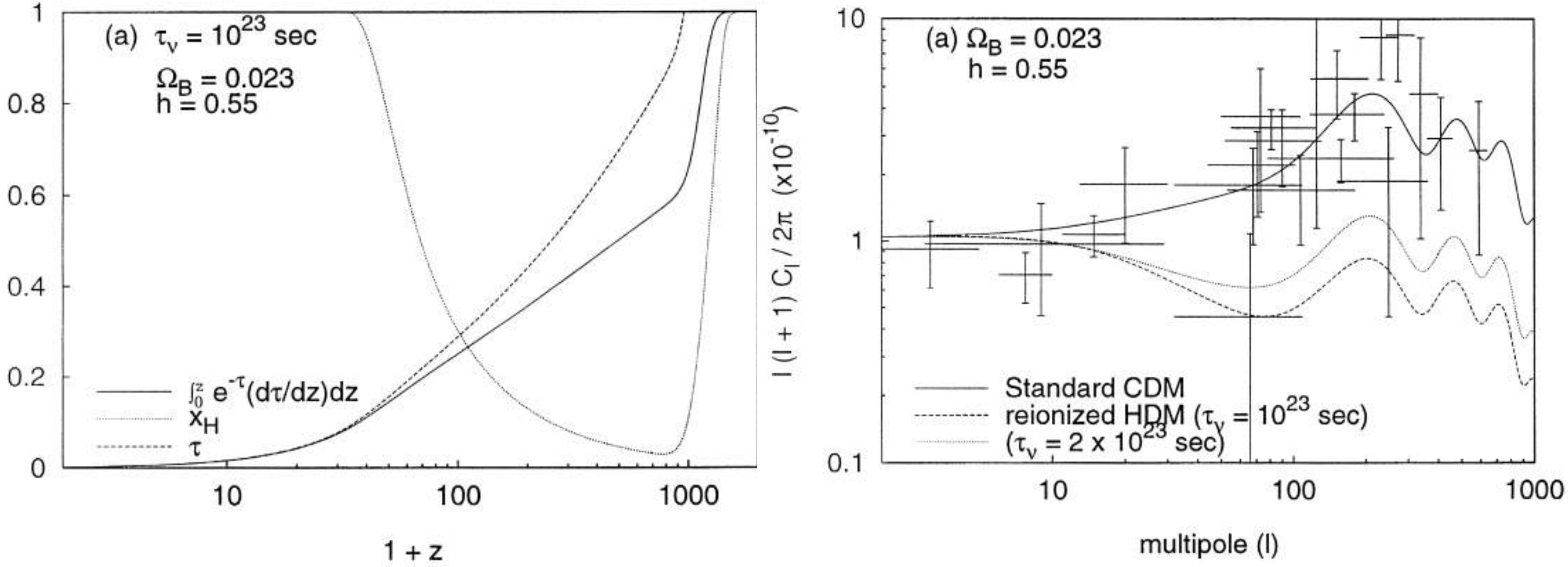
The lifetime is *longer* than the age of the universe so such decays occur too late for the decay photons to be (partially) thermalized and create μ or *y* spectral distortions

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)

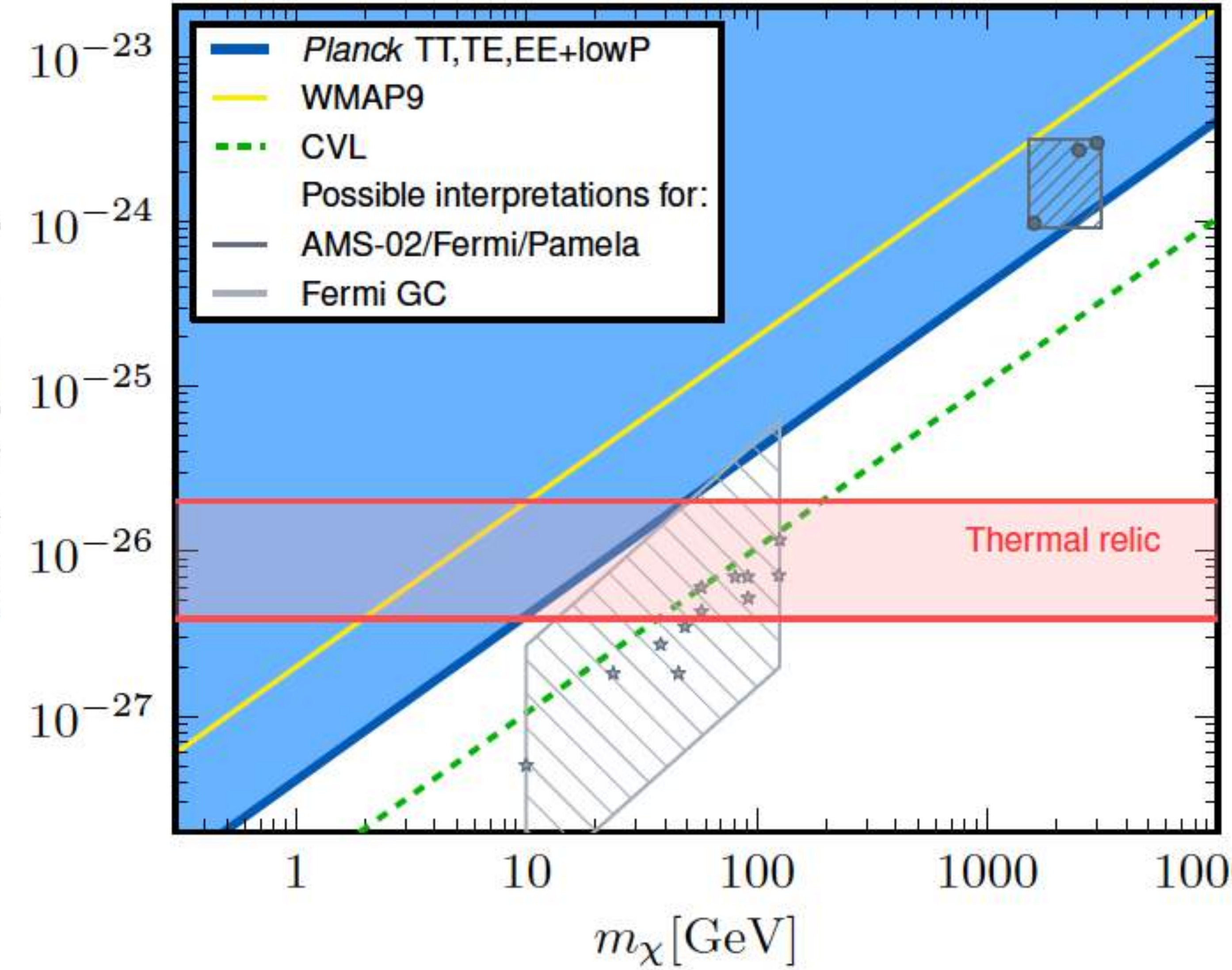
Cosmic microwave background anisotropy in the decaying neutrino cosmology

Adams, Sarkar & Sciama, MNRAS **301**:210,1998

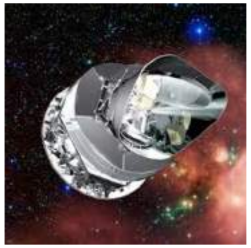


This result is easily generalised to *any* source of ionising photons (E >13.6 eV) *e.g*. generated in the annihilation of dark matter particles (and resulting radiation cascades), and can be strengthened using polarisation (Chen & Kamionkowski, PRD**70**:023502,2004; Padmanabhan & Finkbeiner, PRD**72**:023508,2005; Slatyer, PRD**93**: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

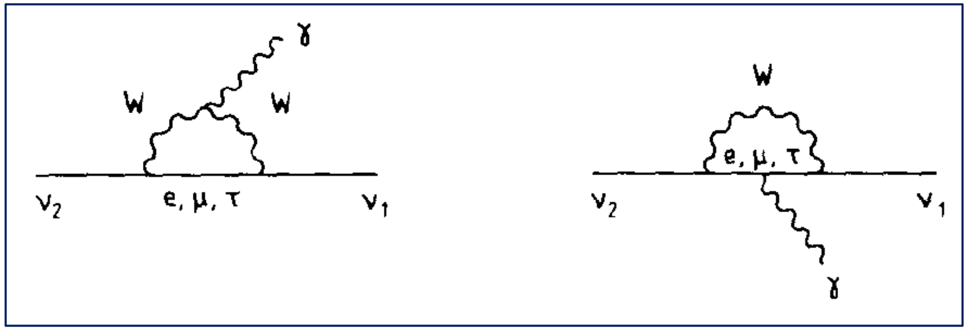


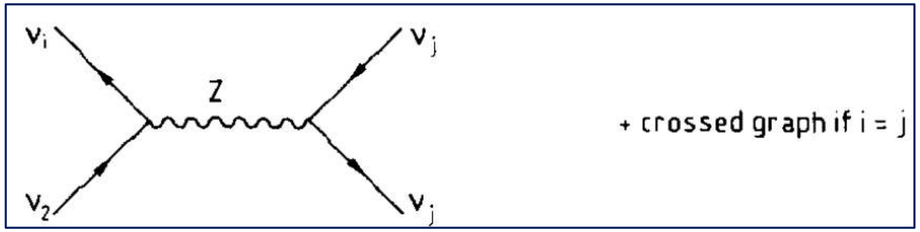
Ade *et al*, A&A **594**:A13,2014



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:

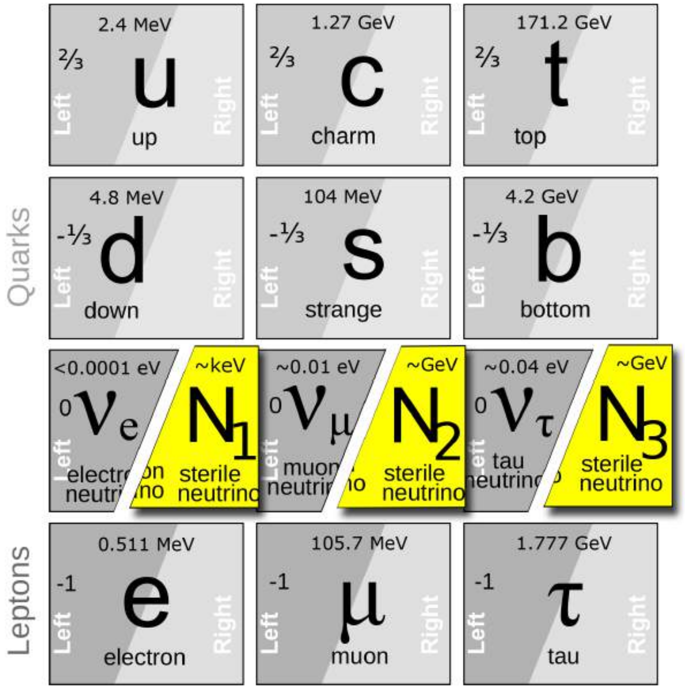


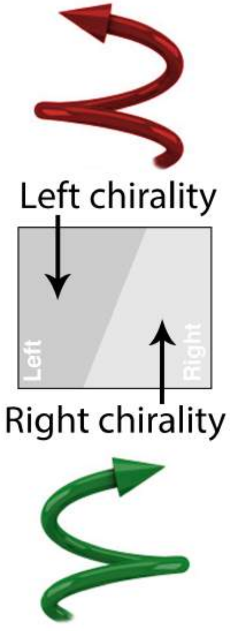


$$\Gamma(x \to \nu\gamma)/\Gamma(x \to \nu\nu\nu) = \frac{27\alpha}{8\pi} = \frac{1}{128}$$

… so invisible decays will *always* be accompanied by visible decays which will affect the CMB and X-ray backgrounds (Barger, Phillips & Sarkar, PL B**352**:365,1995)

Such sterile (right-handed) neutrinos can in principle be the dark matter



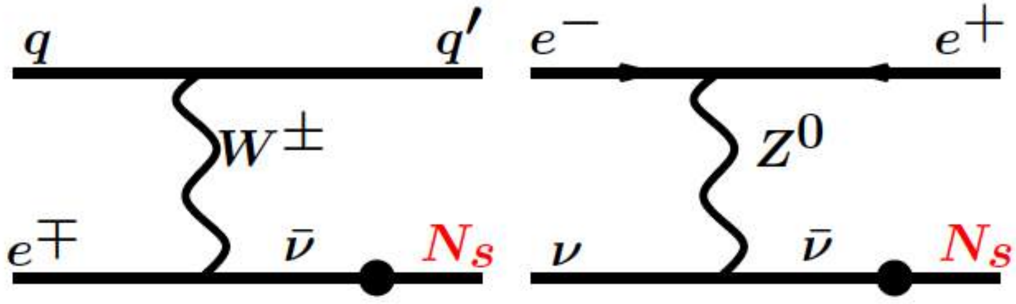


These may mix with the left-handed ‘active’ neutrinos so would behave as super-weakly interacting particles with an effective coupling: $\theta G_{\rm Fermi}$

$$\theta^2_{e,\mu,\tau} \equiv \frac{|M_{\rm Dirac}|^2}{|M_{\rm Majorana}|^2} = \frac{\mathcal{M}_{\rm active}}{\mathcal{M}_{\rm sterile}}$$

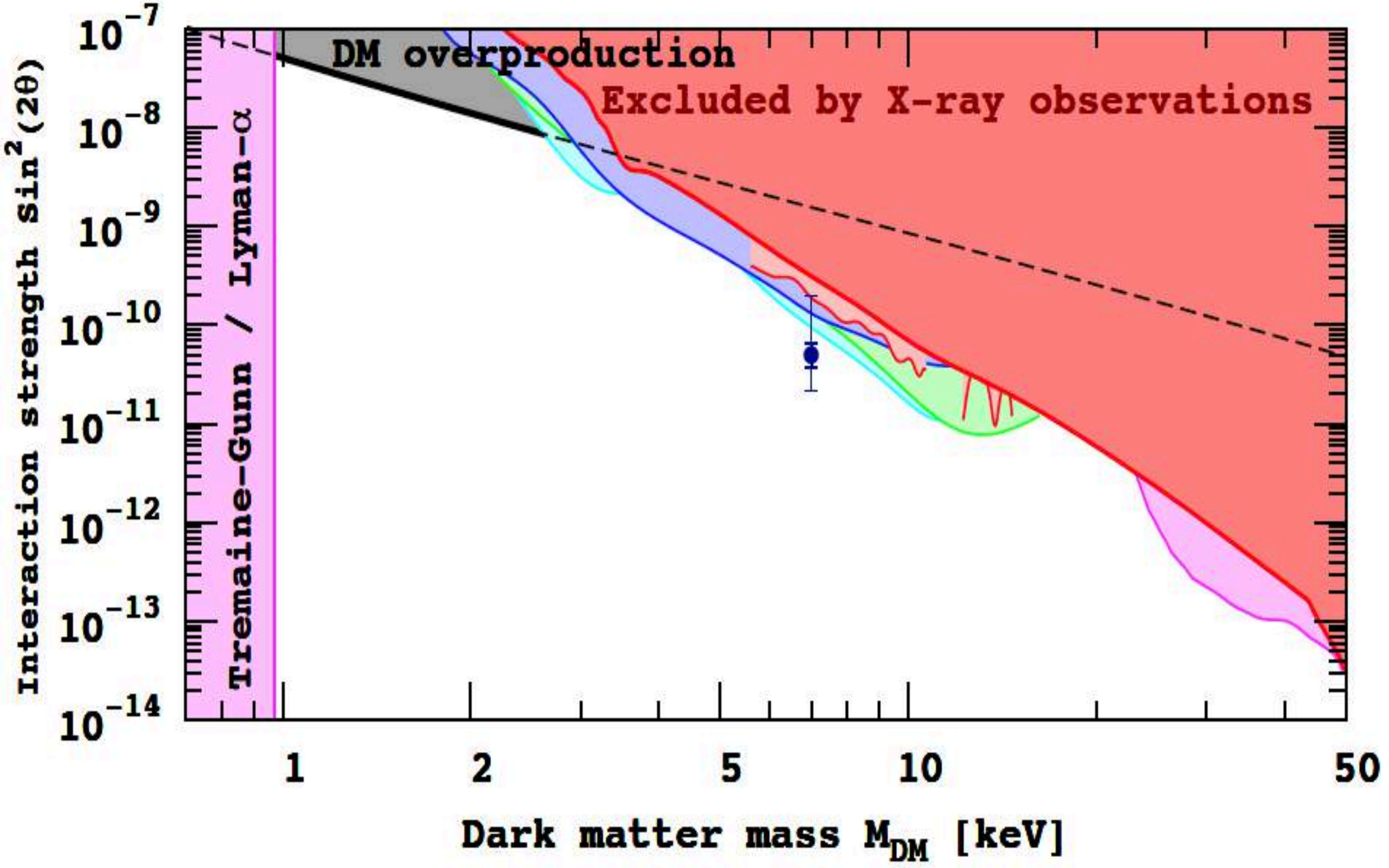
$$\approx 5 \times 10^{-5} \left(\frac{\mathcal{M}_{\rm sterile}}{\rm KeV}\right)^{-1}$$

So they will be created when active neutrinos scatter, at a rate $\propto \theta^2 \Gamma_{\rm active}$



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 ~3.5 keV!



Boyarsky & Shaposhnikov, ARNPS **59**:191,2009
Ruchayskiy *et al*, JCAP 01:025,2018

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 ⇒ shorter lifetimes which can e.g. solve the "Li problem" and be probed via their μ 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

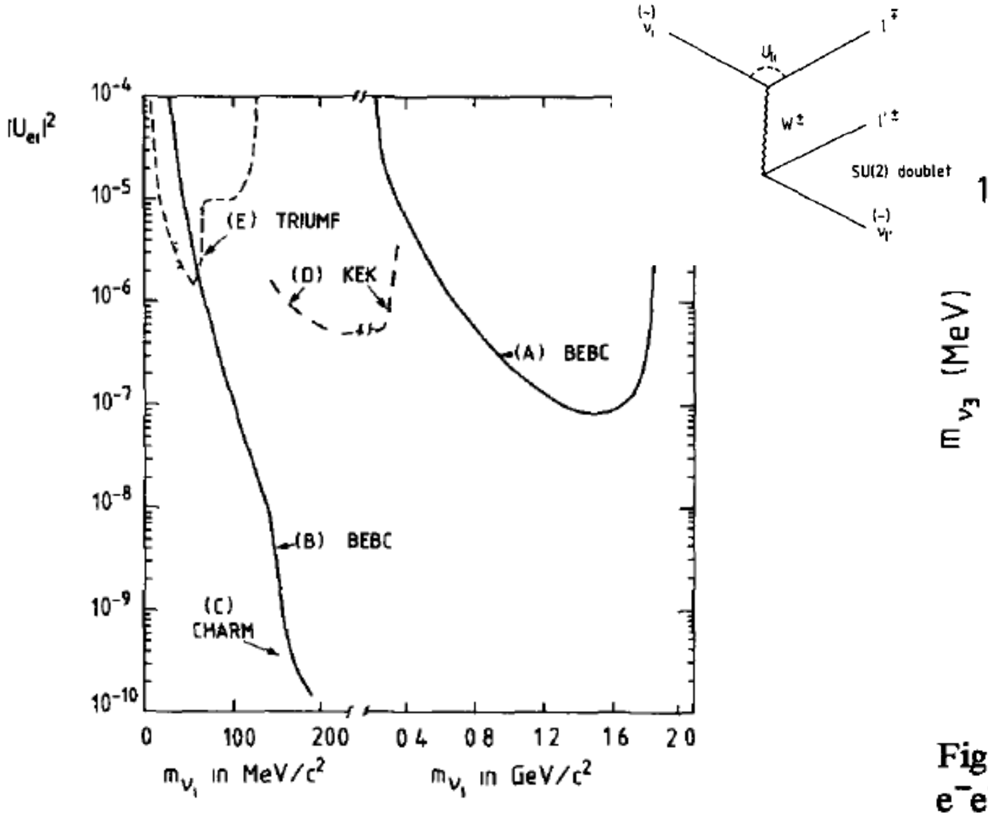


Fig. 3. Upper limits on the leptonic mixing parameter $|U_{ei}|^2$ as a function of neutrino mass $m_{\nu i}$, derived from: Searches for the decays (A) $\nu_i \rightarrow ee\nu, e\mu\nu, e\pi$; (B) $\nu_3 \rightarrow ee\nu, e\mu\nu, e\pi$; (C) $\nu_3 \rightarrow ee\nu$ [6] (uncorrected, see text); searches 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

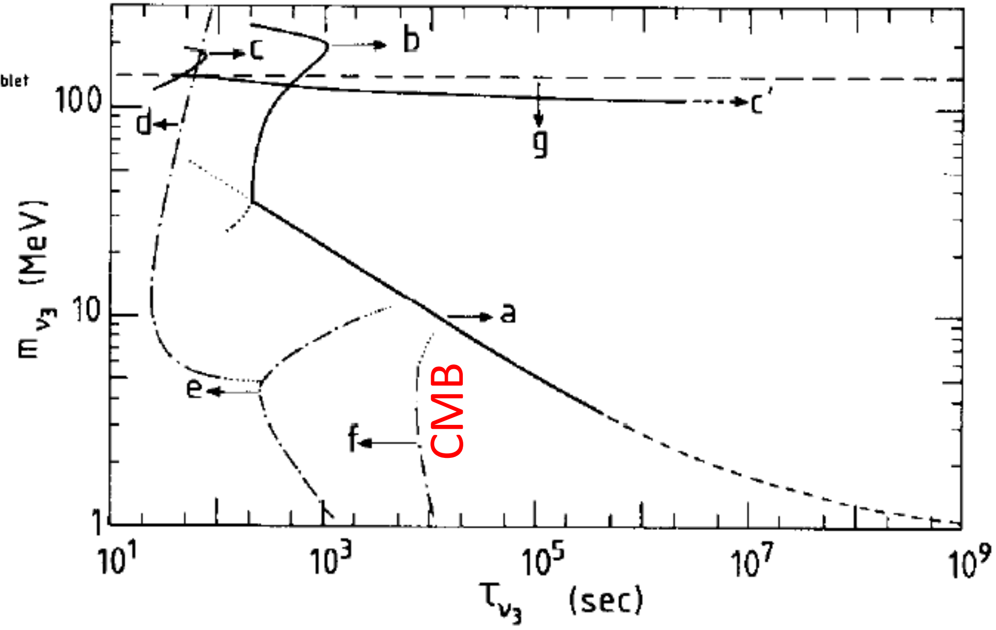


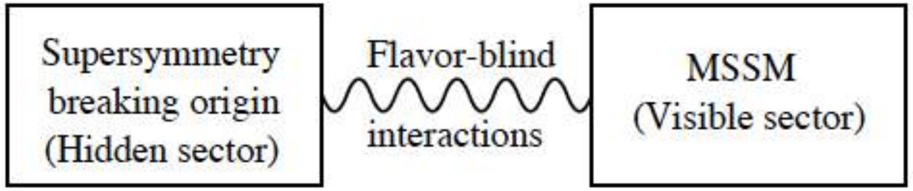
Fig. 2. Experimental lower limits on the lifetime $\tau(\nu_3 \rightarrow e^-e^+\nu_e)$ from: (a) TRIUMF [11], (b) CHARM [12] and on $\tau(\nu_3 \rightarrow \mu^-e^+\nu_e)$ from (c) BEBC [13] and (c') KEK [13]. Cosmological upper limits from: (d) deuterium photofission, (e) primordial nucleosynthesis, (f) black-body background. There is no allowed region below (g), the MARK II [3] upper bound on m_{ν_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

$$\tilde{G} \to \gamma\tilde{\gamma}$$



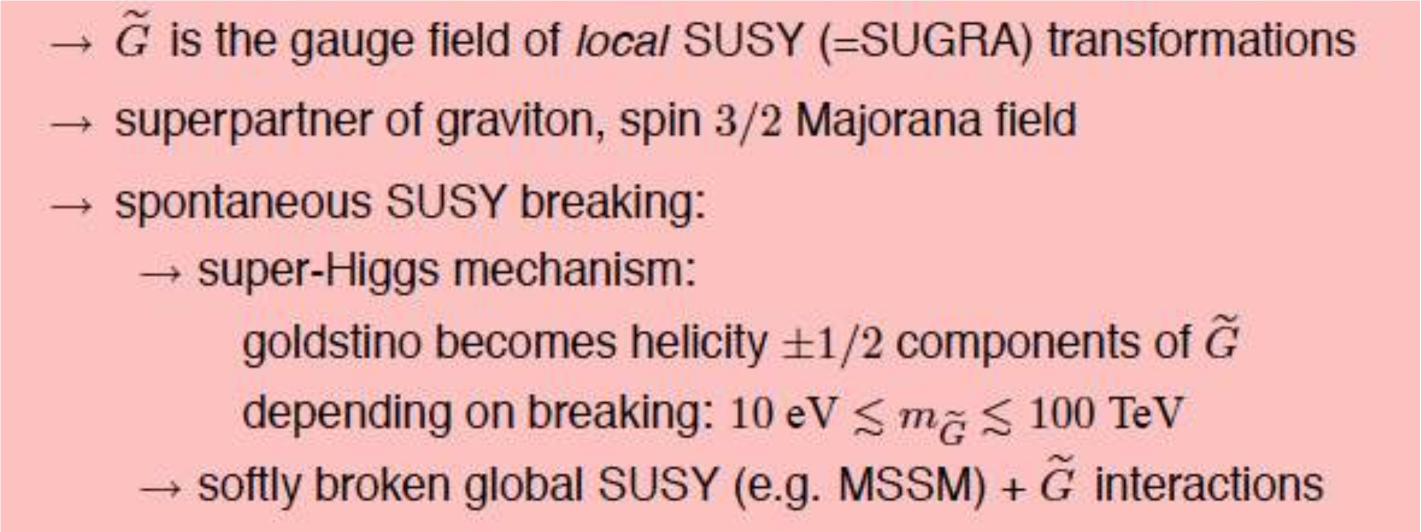
Supersymmetry breaking origin (Hidden sector)

Flavor-blind interactions

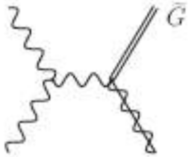
MSSM (Visible sector)

$$\tau_{3/2} \approx 4\times10^{5}\ \mathrm{s}\left(\frac{m_{3/2}}{1\ \mathrm{TeV}}\right)^{-3}$$

Weinberg 1982; Khlopov & Linde 1983; Krauss 1983; Ellis, Kim & Nanopoulos 1984, Moroi 1985



- → $\tilde{G}$ 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 $\pm 1/2$ components of $\tilde{G}$
    depending on breaking: $10\ \mathrm{eV} \lesssim m_{\tilde{G}} \lesssim 100\ \mathrm{TeV}$
  - → softly broken global SUSY (e.g. MSSM) + $\tilde{G}$ interactions



Post-inflation generation by 2➛2 scatterings in thermal bath: $n_{3/2} \sim T_R/M_P$

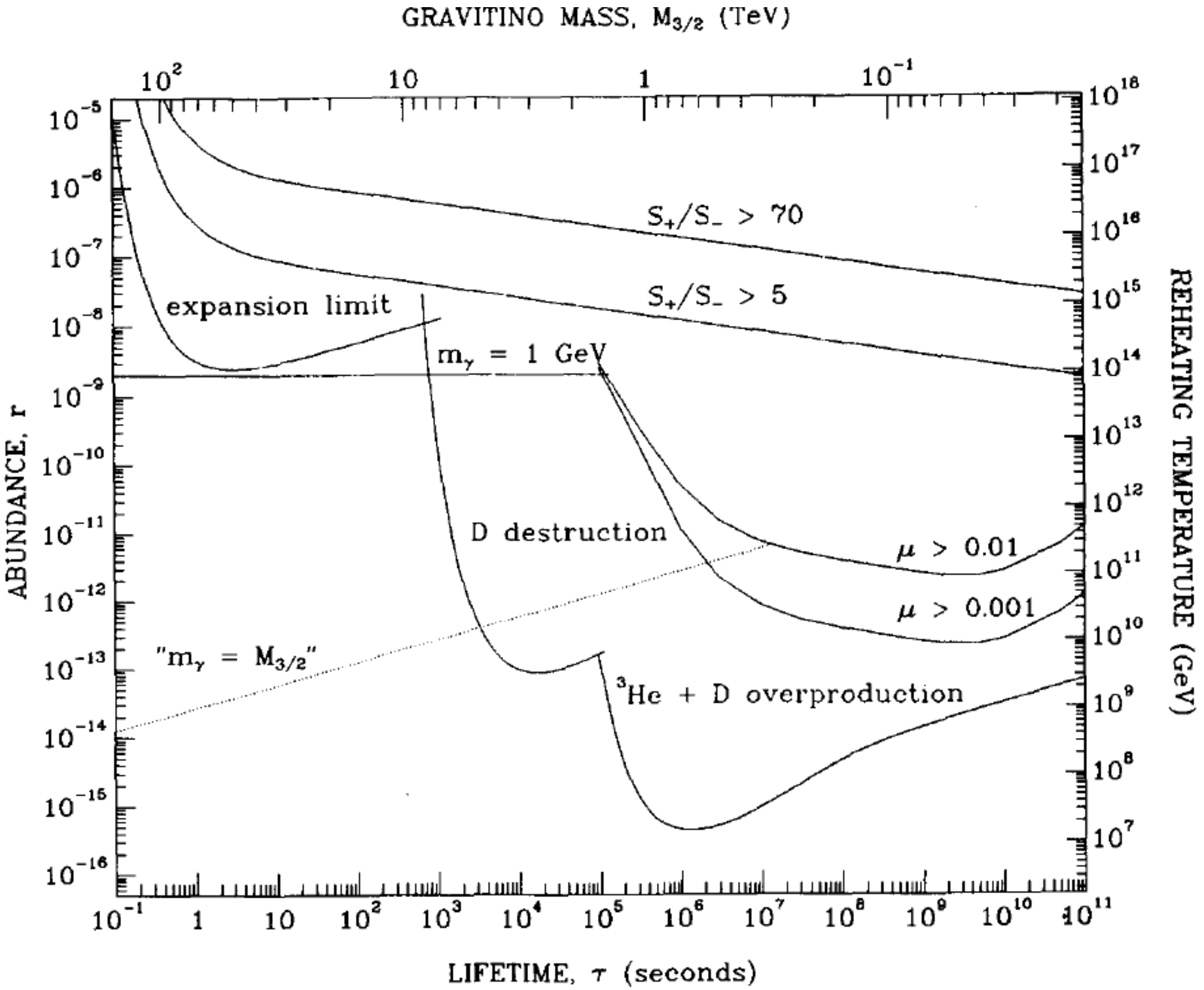
… these are dangerous relics as they can decay *after* BBN and CMB thermalisation

The high energy photons trigger radiation cascades in the background plasma which can photo-dissociate the synthesized light elements and induce μ and y distortions in the CMB spectrum

⇒ **limit on the decaying gravitino abundance** (and correspondingly on the reheat temperature)

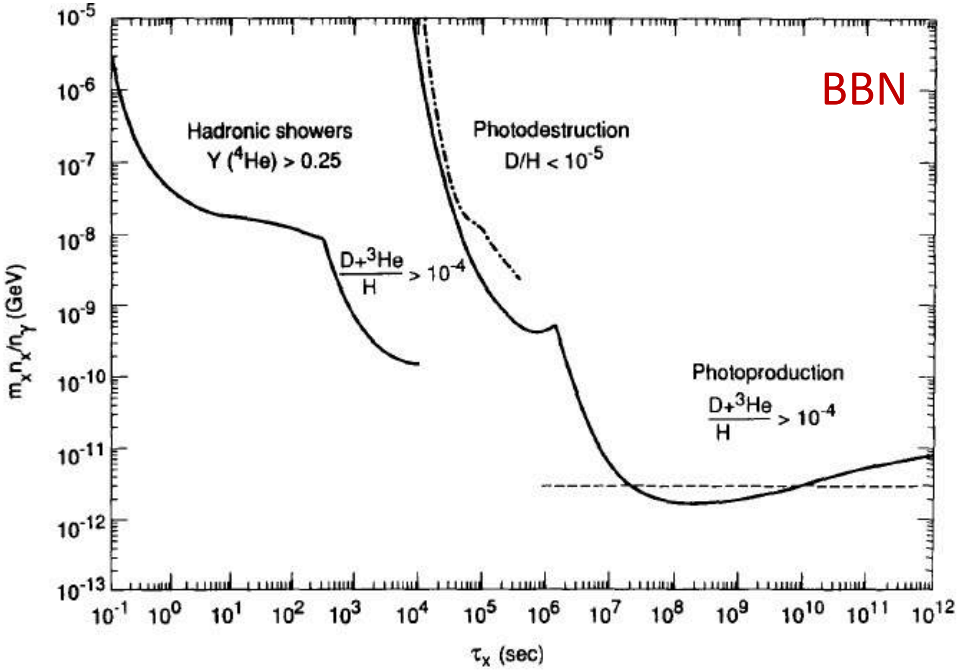
Ellis, Nanopoulos, Sarkar, Nucl.Phys.**259**:175,1985; Juszkiewicz, Silk, Stebbins, PL **158**B:463,1985

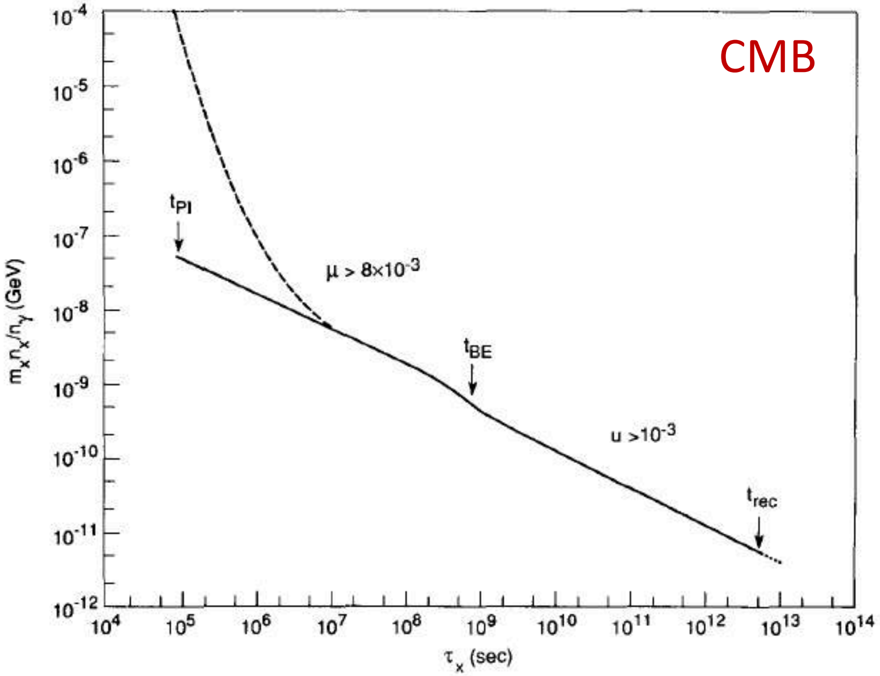
Most severe constraint from considering photofission of ^{4}He ➛ (*much* rarer) D, ^{3}He

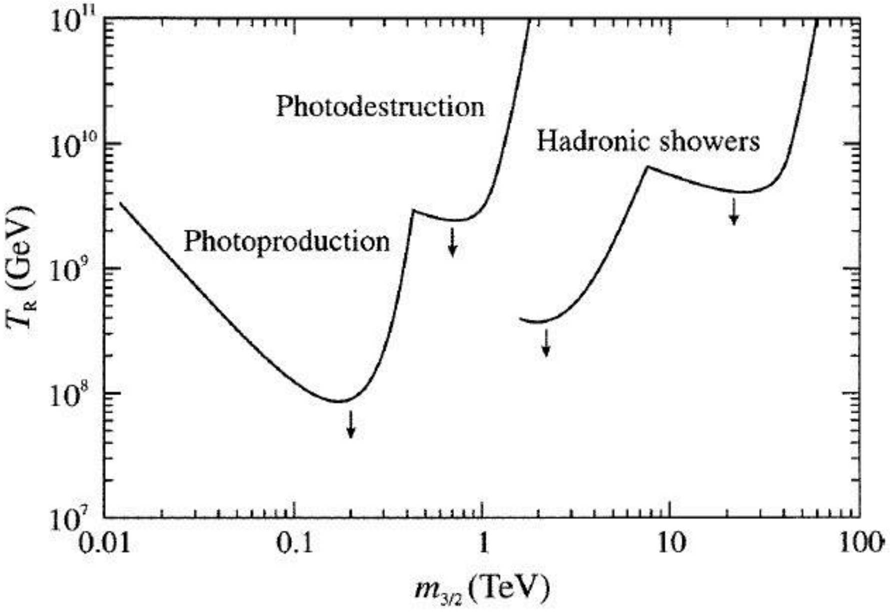


… can be generalised to any decaying particle (and updated with future limits on μ and y)

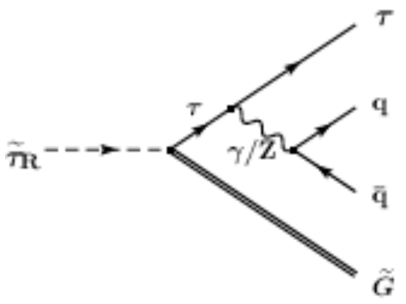
This implied a *severe* upper limit on the reheat temperature following inflation - which ruled out the possibility of GUT-scale baryogenesis … and motivated attempts to create the observed baryon asymmetry at lower temperatures ➞ leptogenesis (Ellis *et al*, Nucl.Phys. B**373**:399,1992)



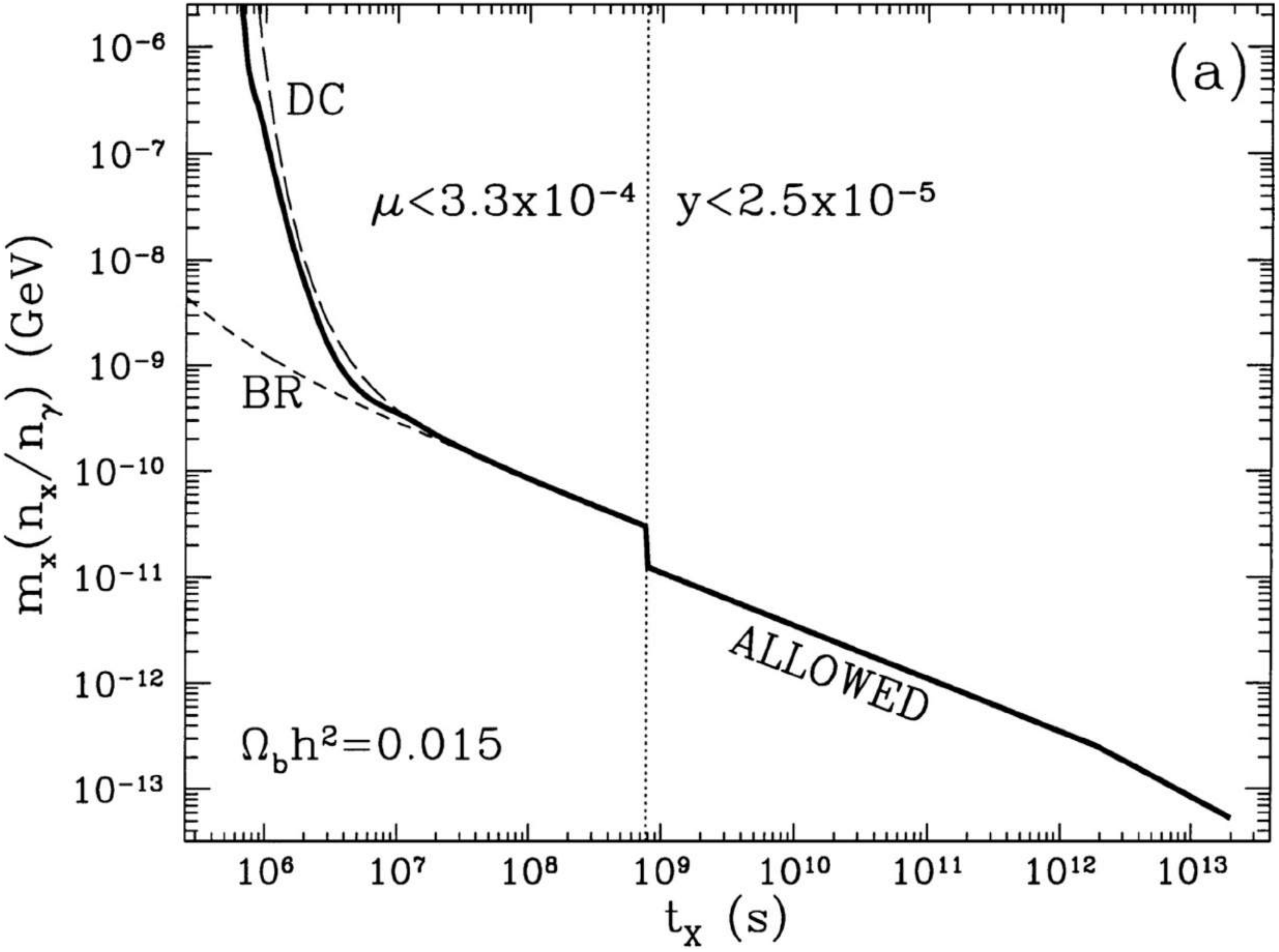




If the gravitino is in fact the LSP, then the bound on the reheat temperature is relaxed … but similar constraints then apply to the NLSP decays

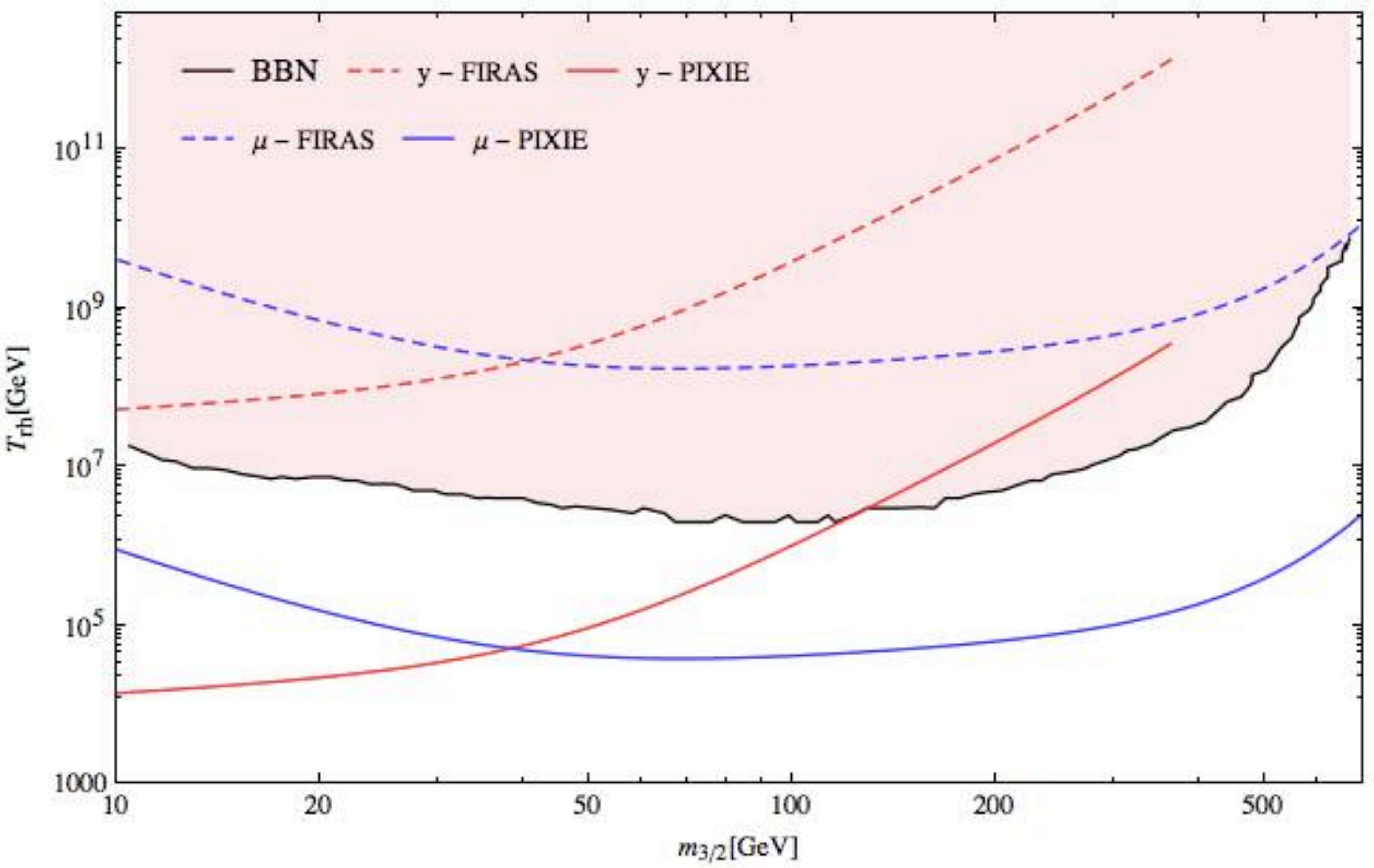


FIRAS vastly improved the constraints on visibly decaying particles

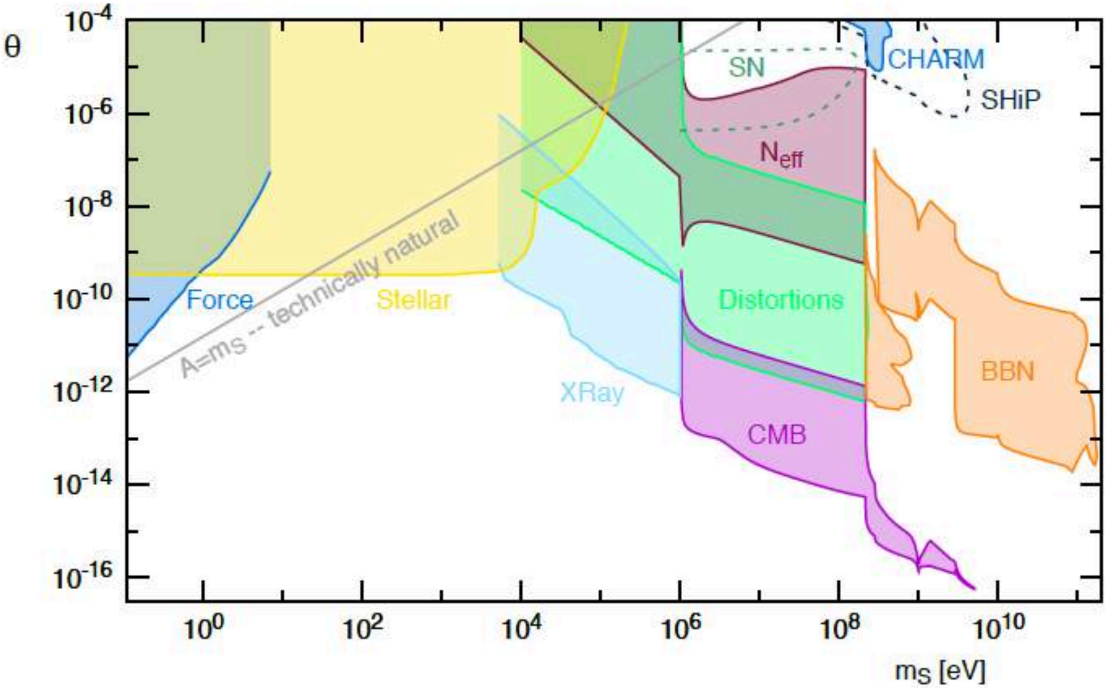


Ellis *et al*, NP B**373**:399,1992, Hu & Silk, PR D**48**:485,1993

Reexamination of these arguments have lowered the reheat temperature bound (e.g. Kawasaki, Kohri, Moroi, Takaesu, PR D**97**:023502,2018) and the PIXIE sensitivity will probe to even lower temperature (Dimastrogiovanni, Chluba, Krauss, PRD**94**:023518,2016)



Another well-motivated metastable relic particle is a scalar singlet coupled to the SM via a (super-renormalisable)‘Higgs portal’: $\mathcal{L}_{H/S} = \mu^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 - \frac{m_S^2}{2} S^2 - A S H^\dagger H$

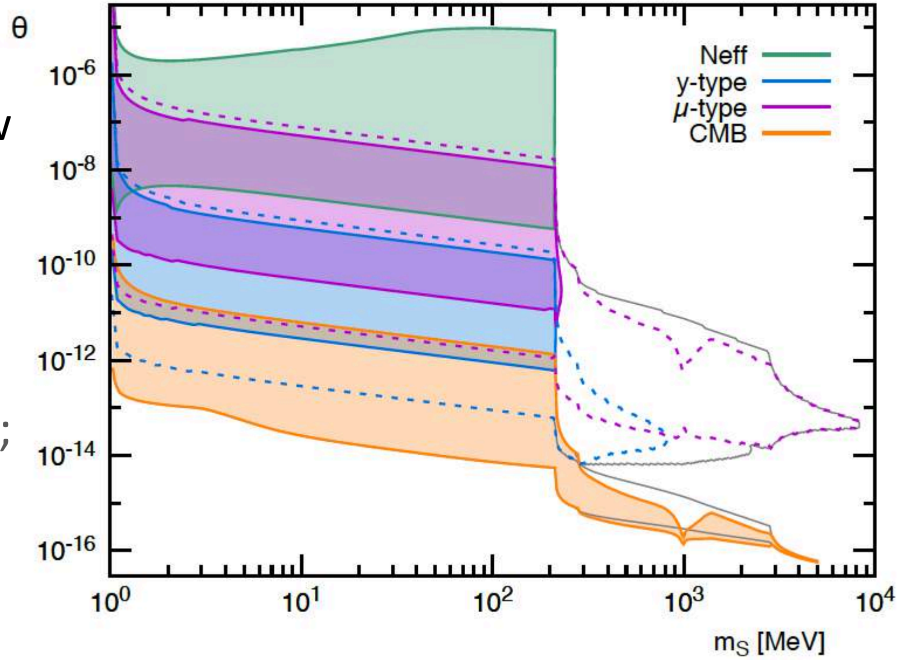


The mixing angle between the physical states is: $\theta = \frac{Av}{m_h^2 - m_S^2}$

In the limit that $\theta \to 0$, 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 ‘freeze-in’)

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