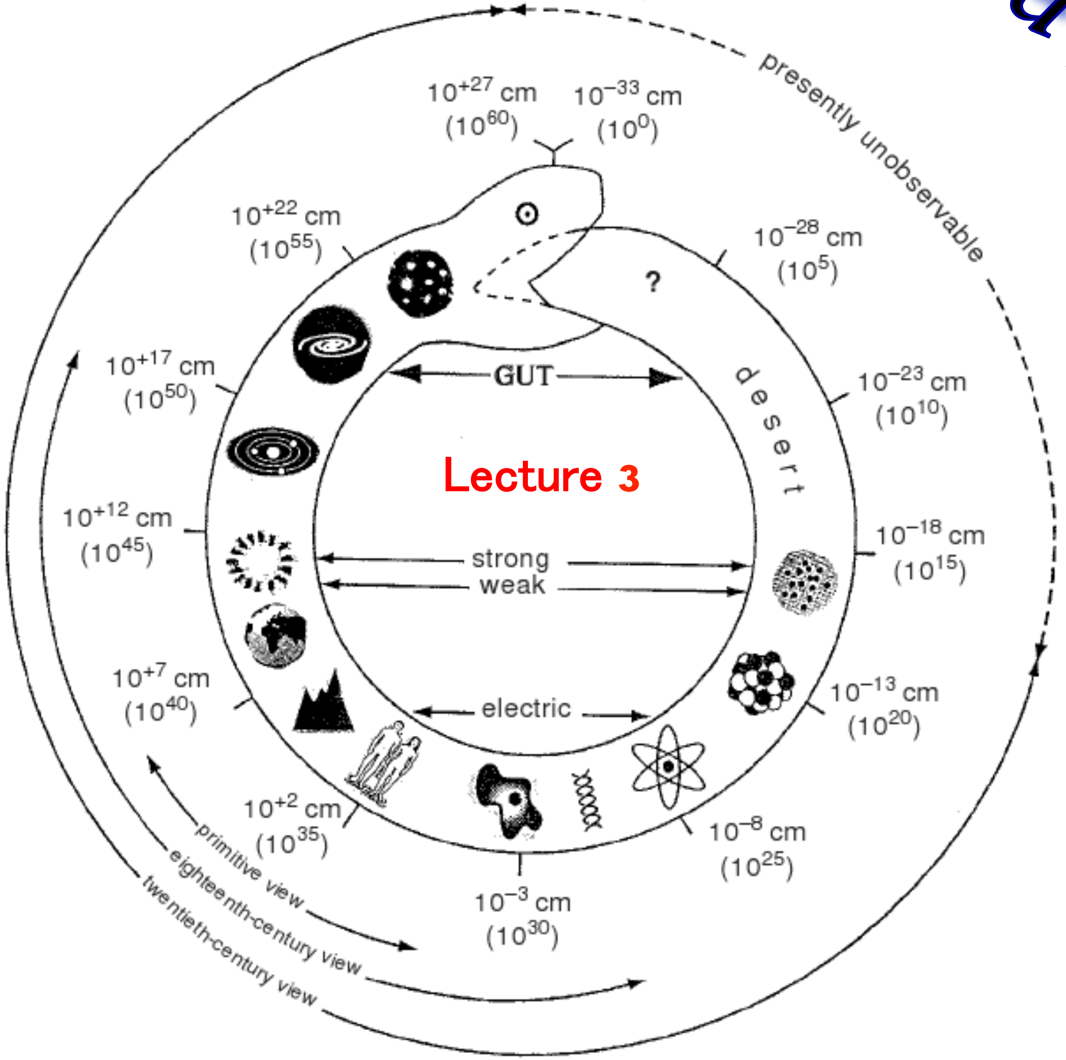
Oxford Physics

The Niels Bohr International Academy

Physics of the early universe

Subir Sarkar

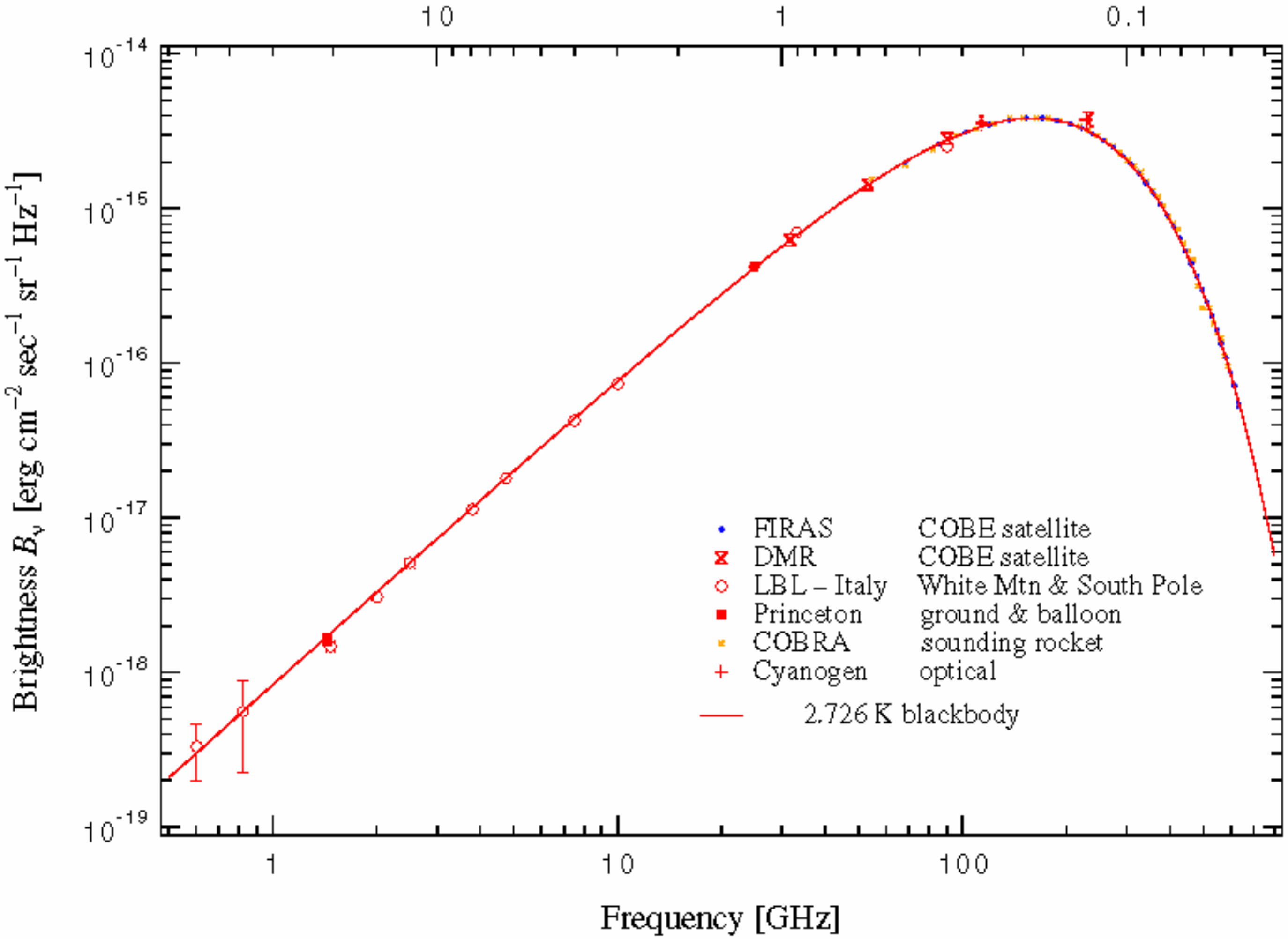


Lecture 3

ICTP Summer School on Particle Physics, 15-26 June 2015, Trieste

The Abdus Salam International Centre for Theoretical Physics

The **blackbody** spectrum of the CMB is testimony to our hot, dense past and demonstrates directly that the expansion was **adiabatic** (with negligible energy release) back at least to $t \sim 10^6$ s



Fixsen, ApJ **707**:916,2009

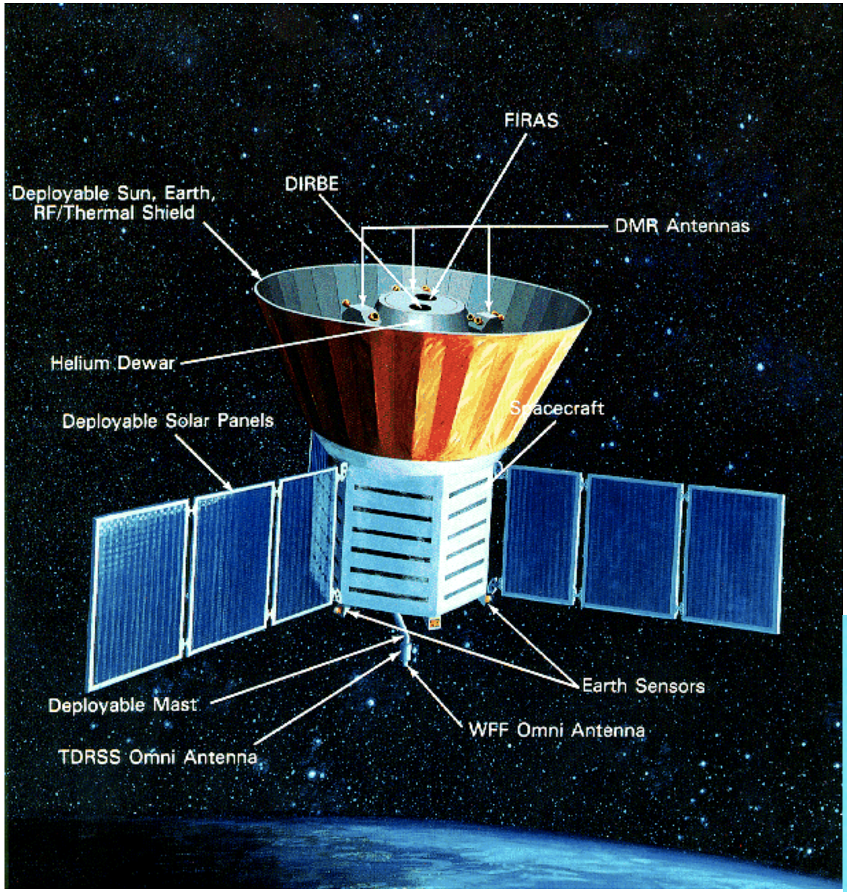
To derive this quantitatively, we need to understand how **thermalisation of the radiation** occurred in the early universe

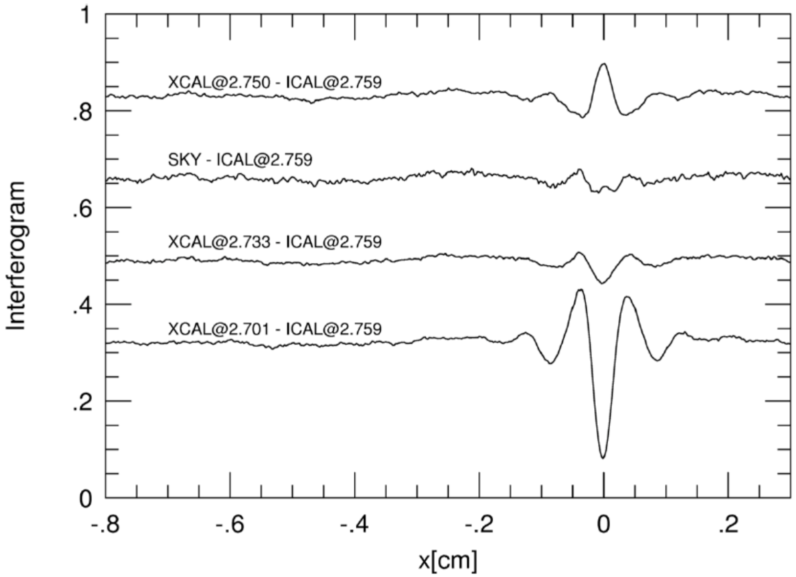
Far Infra Red Absolute Spectrophotometer

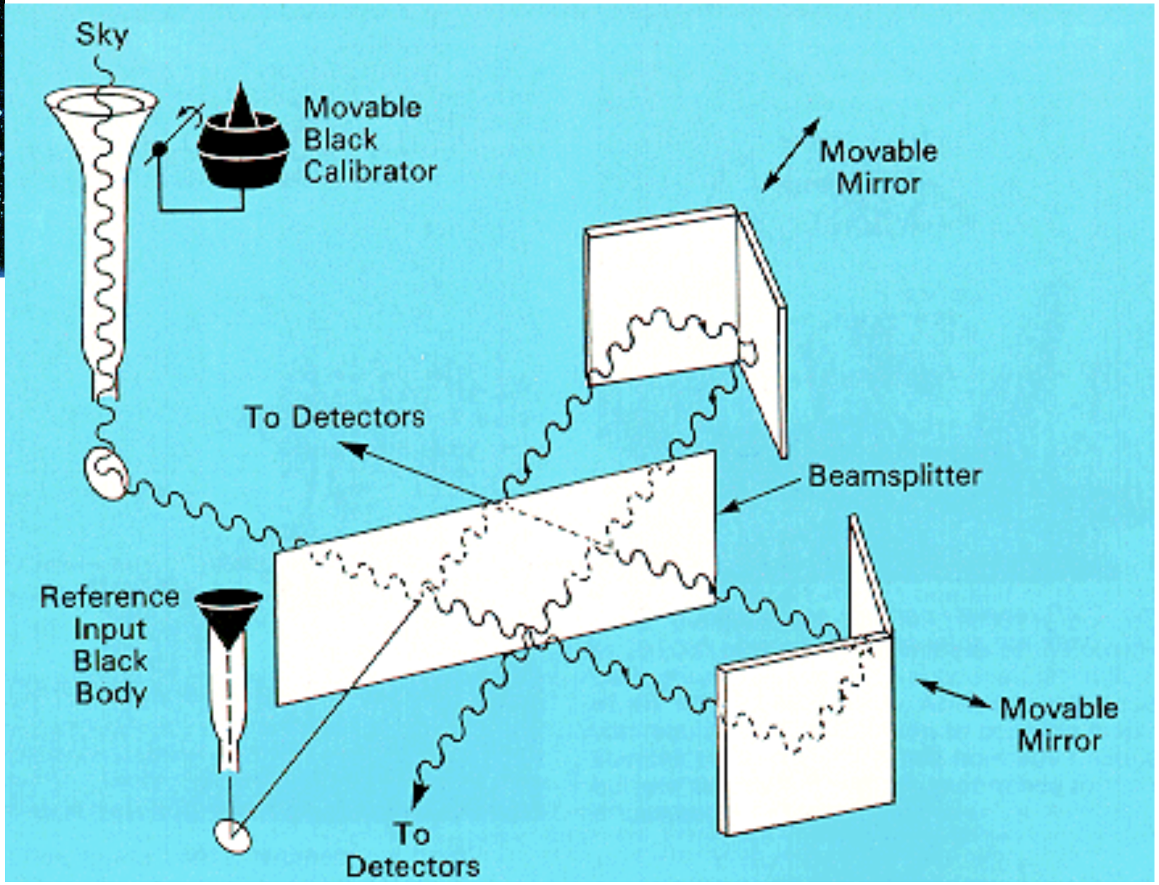
(differential polarizing Michelson interferometer)

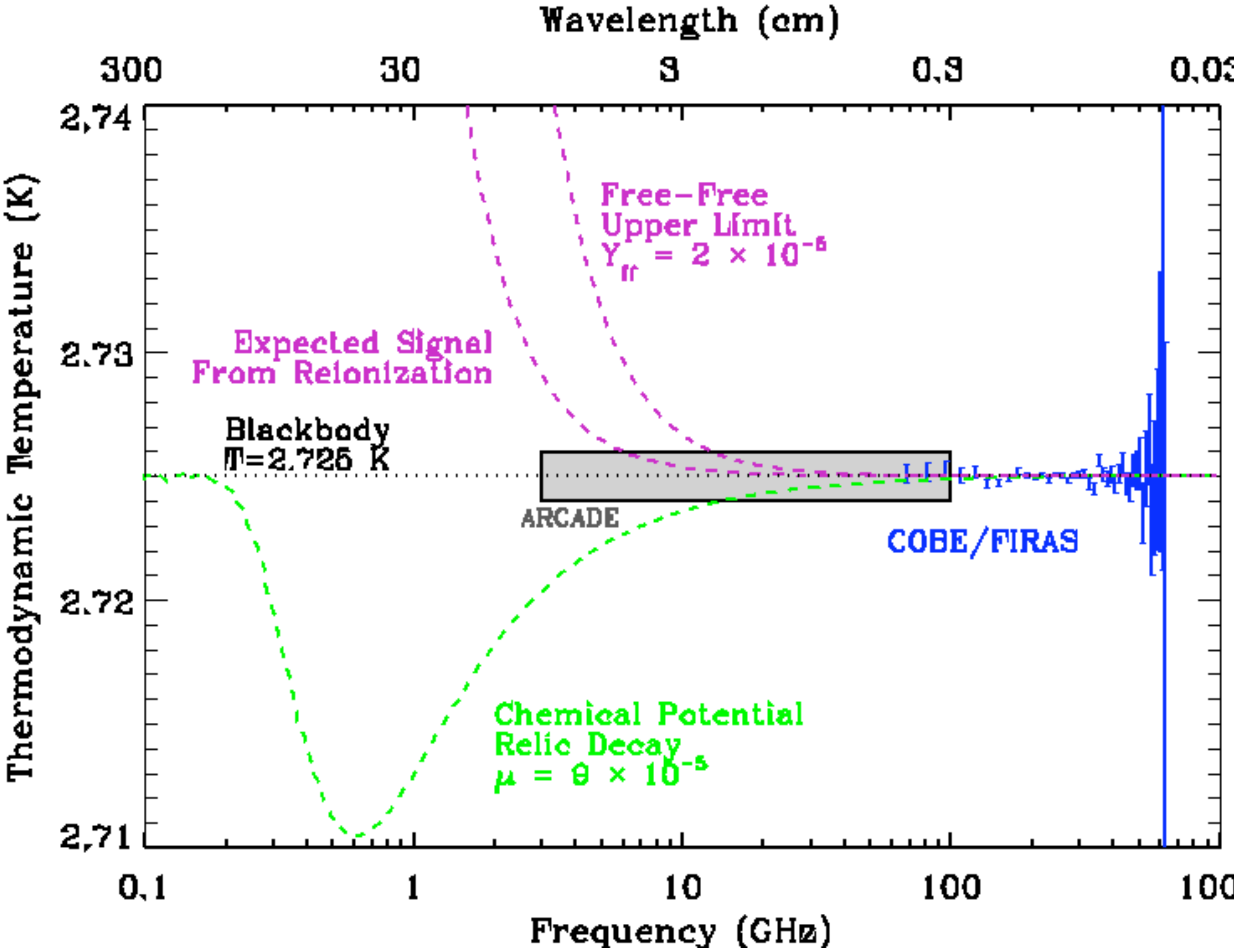
compares sky temperature with internal *calibrated* blackbody (John Mather → Nobel prize 2006)

→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:

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

For a pedagogical derivation, see Peebles (*Principles of Physical Cosmology*, 1993)

The stationary solutions $\partial n/\partial y = 0$ are general Bose-Einstein thermal distributions:

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

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

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

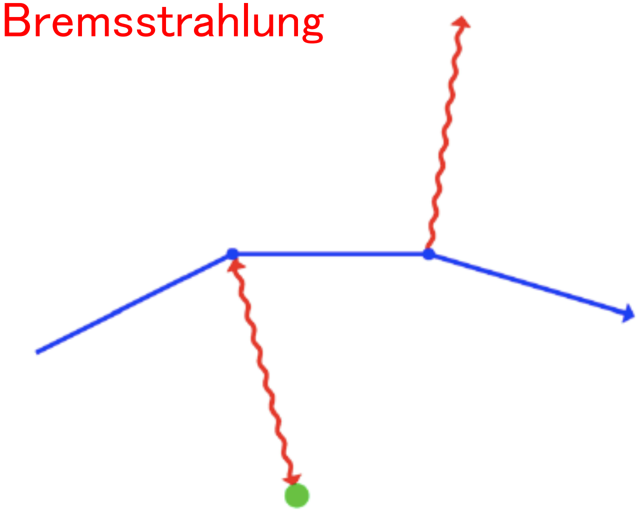
$$\frac{\Delta U}{U} = \left(\frac{4\zeta(2)}{3\zeta(3)} - \frac{\zeta(3)}{\zeta(4)}\right)\mu = 0.714\mu.$$

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

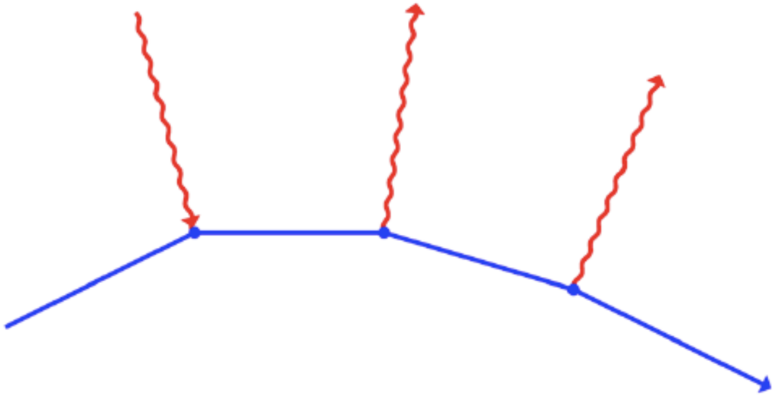
$$\Delta U/U < 6 \times 10^{-5}$$

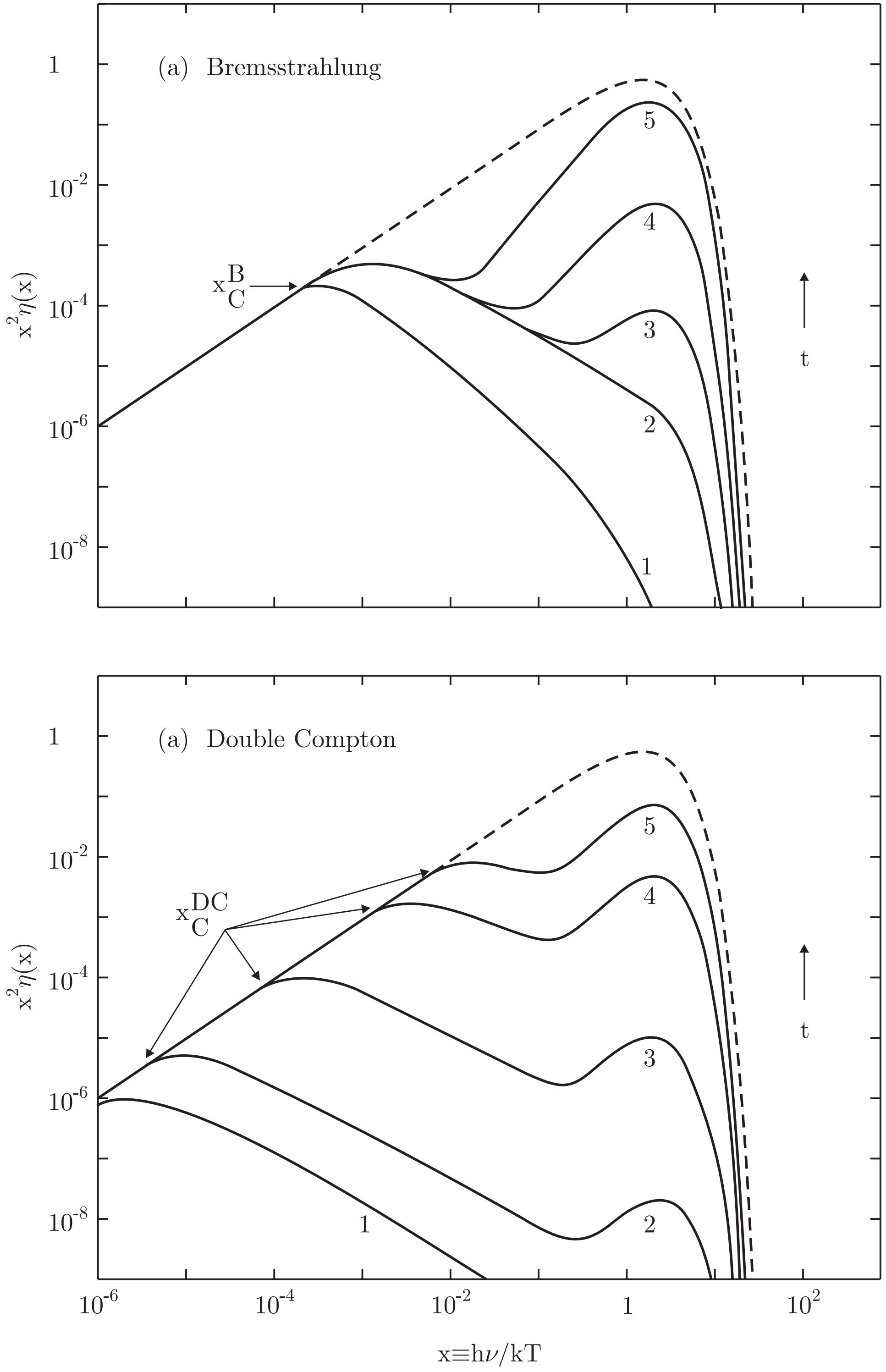
To reduce $\mu \to 0$ requires the *creation* of photons i.e. radiative processes

Bremsstrahlung



Double Compton scattering



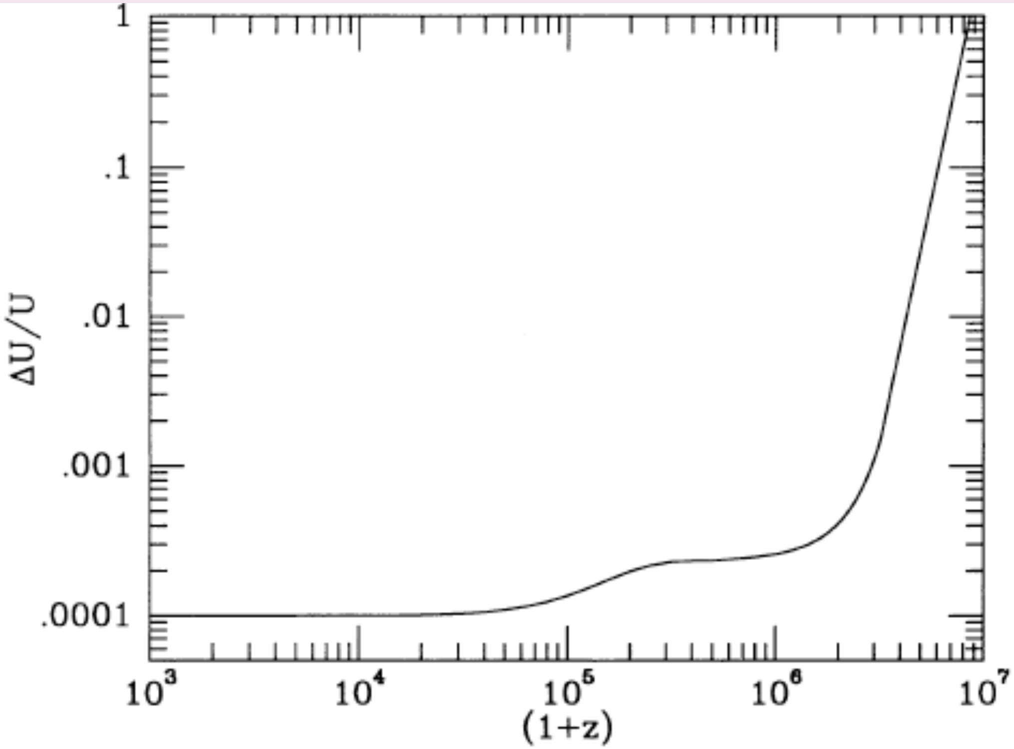


Since $(1+z)\partial y/\partial z \propto \Omega_B h^2 (1+z)^2$, the overall rate for eliminating a μ distortion scales like $\Omega_B h^2 (1+z)^{5/2}$ per Hubble time. A proper consideration (Burigana *et al.* 1991, ApJ, 379, 1-5) of this interaction of the photon creation process with the Kompaneets 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 $\Omega_B h^2 = 0.0224$.

The absence of a μ or y distortion implies the following constraint on any em energy release ...



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

Decoupling of the relic radiation

Thomson scattering on electrons: $\gamma + e \rightarrow \gamma + e$

Photon interaction rate ($x = n_p/n_B$): $\Gamma_{\text{Thomson}} = n_e \langle \sigma_T |v| \rangle \propto x_e T^3 \sigma_T$

cf. expansion rate of the universe (MD era): $H \propto T^{3/2}$

$\Gamma_{\text{Thomson}} > H \Rightarrow$ Photons/matter in equilibrium

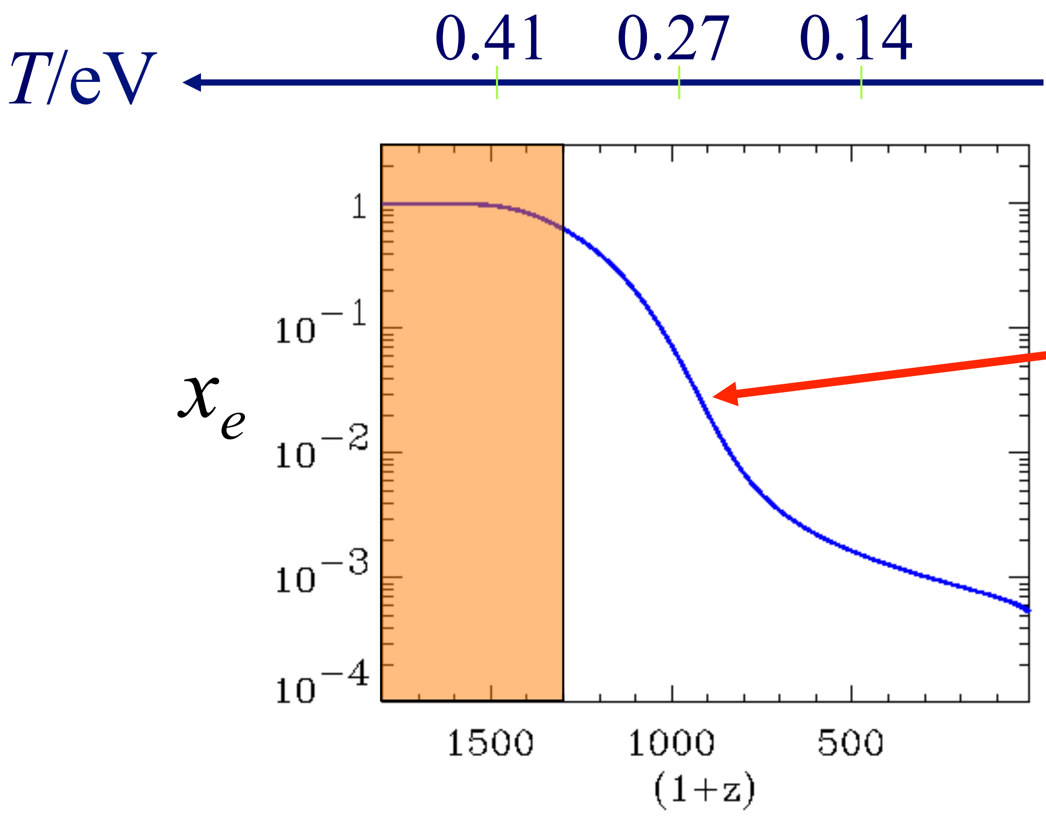
$\Gamma_{\text{thomson}} < H \Rightarrow$ Photons/matter decouple

The ionisation fraction x_e drops rapidly at (re)combination so the Thomson scattering rate also decreases sharply below the Hubble expansion rate …
This defines a ***last scattering surface*** for the relic photons, which we see today as the **cosmic microwave background**

While $p + e^- \longrightarrow \mathrm{H} + \gamma$ is in **chemical equilibrium**, $\mu_p + \mu_e = \mu_{\mathrm{H}}$ (since $\mu_\gamma = 0$) so,
$n_{\mathrm{H}} = (g_{\mathrm{H}}/g_p g_e) n_p n_e (m_e T/2\pi)^{3/2}\, \mathrm{e}^{B/T}$ (where $B = m_p + m_e - m_{\mathrm{H}} = 13.6$ eV)

In terms of the ionisation fraction x_e and the baryon-to-photon ratio, $\eta = n_B/n_\gamma$, this is the Saha ionisation equation:

$$\frac{1 - x_e}{x_e^2} = \frac{4\sqrt{2}\zeta(3)}{\sqrt{\pi}} \eta \left(\frac{T}{m_e} \right)^{3/2} \mathrm{e}^{-B/T}$$

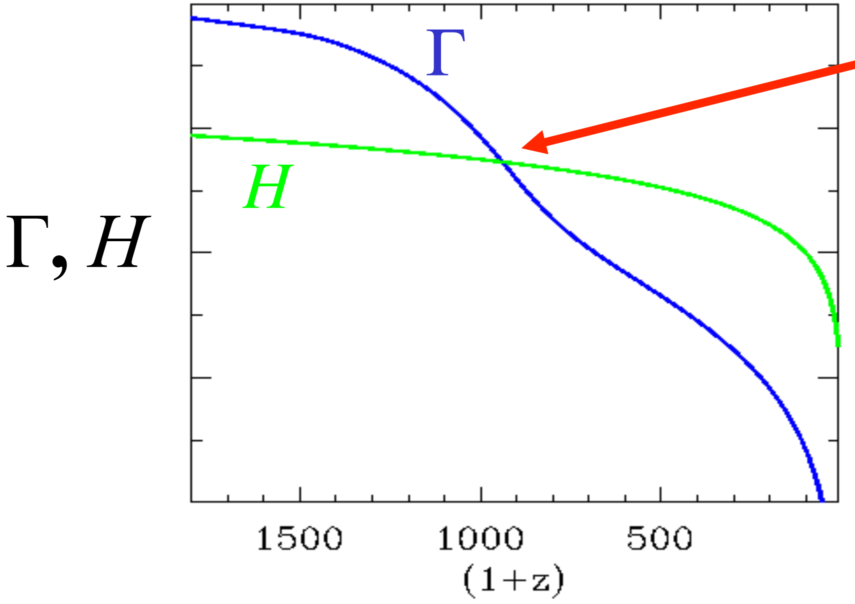


Decoupling/recombination happens not at $T \sim 13.6$ eV but at $T \sim 13.6$ eV/-ln(η)

(Re)combination

(according to the Saha ionisation equation)

$T_{\text{rec}} \sim 0.35$ eV, $z_{\text{rec}} \sim 1300$



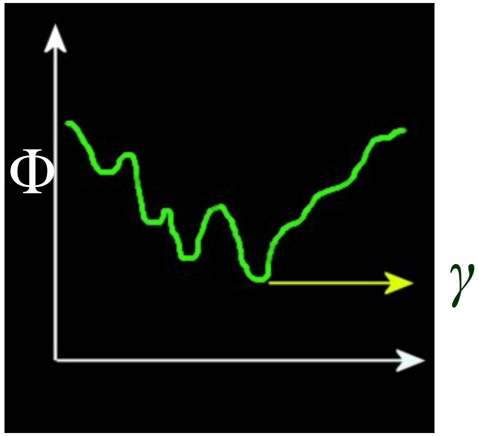
Decoupling

(of photons and baryons)

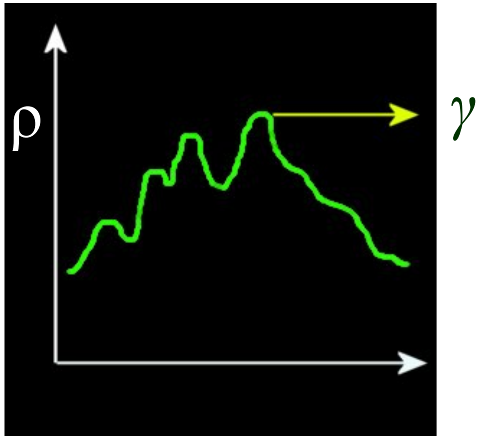
$T_{\text{rec}} \sim 0.29$ eV, $z_{\text{dec}} \sim 1100$

More precise calculation by
Seager *et al*, ApJ **523**:L1,1999
(Codes: *CosmoRec*, *HyRec*)

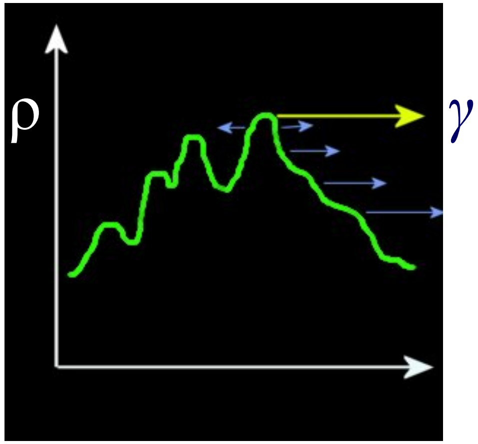
Fluctuations in the CMB temperature ⇒ fluctuations in the matter density



Photons are *redshifted* as they move out of gravitational potential wells



Dense regions have higher temperature ⇒ photons have higher energy (*blue*shift)



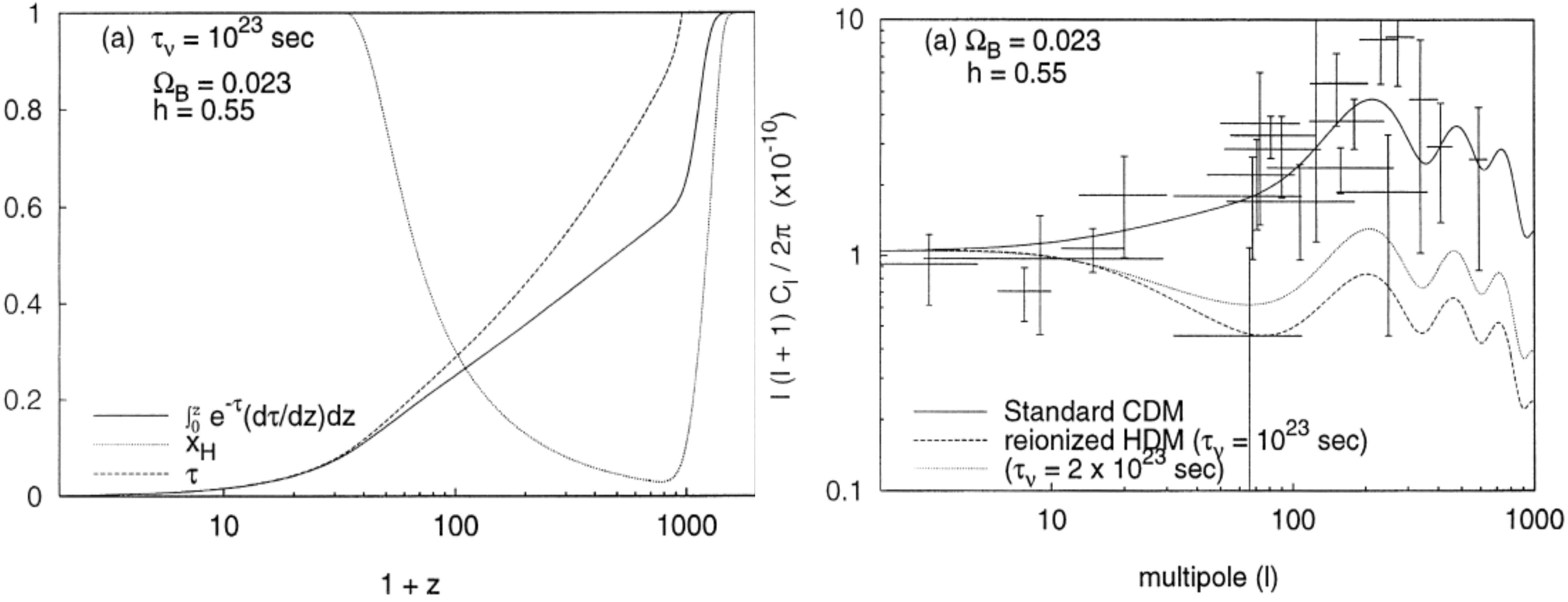
Photons emitted from a moving surface are *red*/*blue*-shifted

Fortunately the effects do not *quite* cancel so the CMB carries a memory of the past!

However there is no effect on the CMB spectrum!

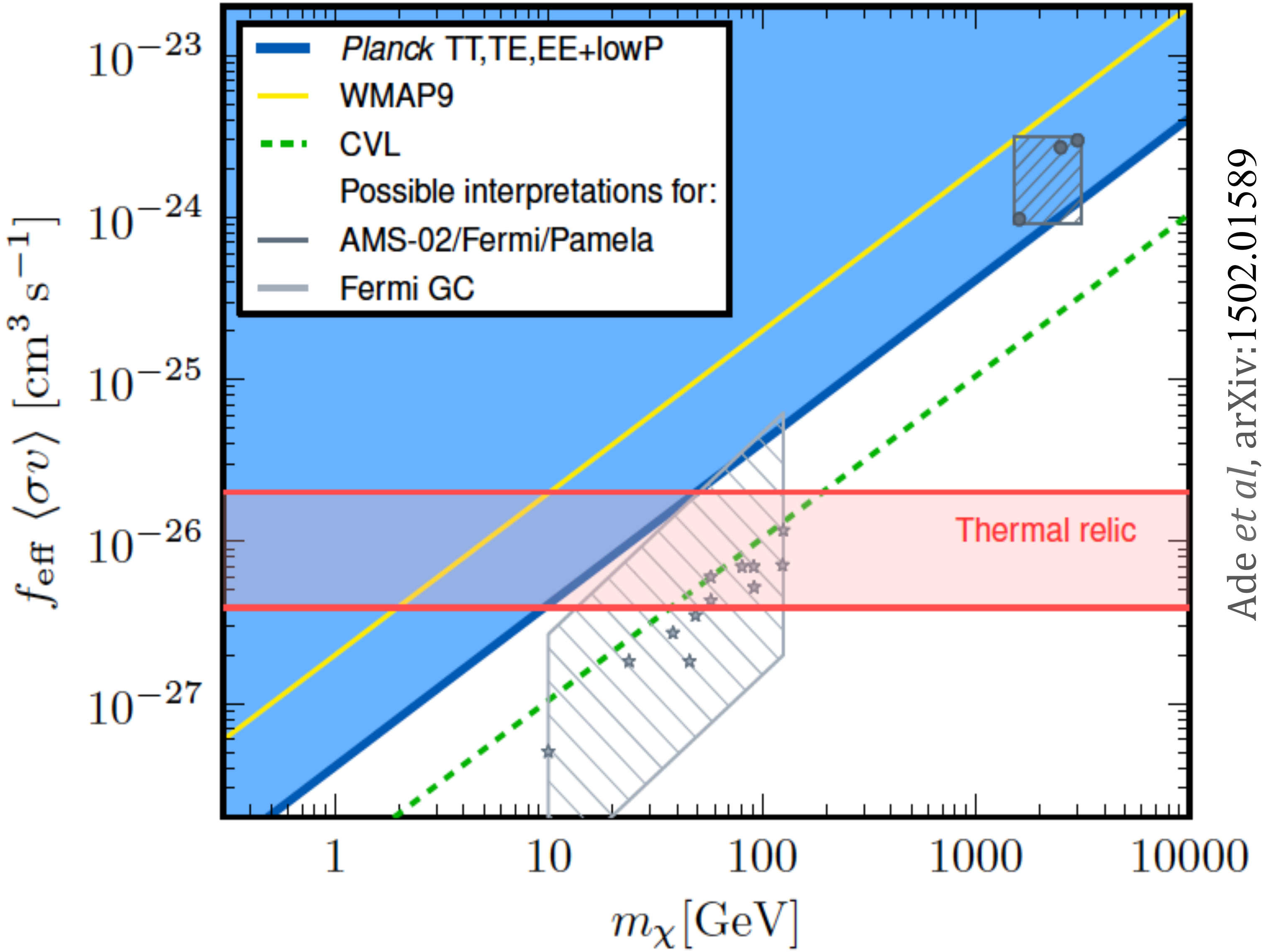
DM annihilation/decay energy release would increase the ionisation fraction of the intergalactic medium and broaden the ‹last scattering surface› of the CMB

This would result in damping of the ‘acoustic’ peaks in the power spectrum of CMB fluctuations – as was noted originally for decaying dark matter



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

The results are easily generalised to *any* source of ionising photons (E >13.6 eV) e.g. generated in the annihilation of dark matter particles (and resulting cascade)

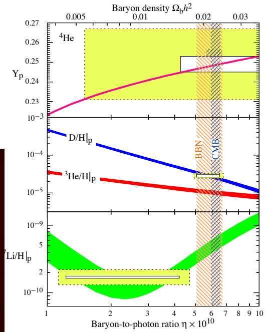


Ade *et al*, arXiv:1502.01589

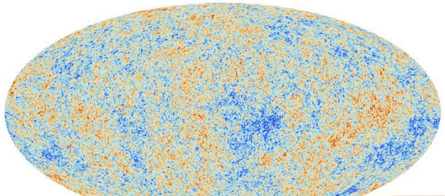
Now that the CMB TT power spectrum is known to O(%) accuracy, *Planck* data sets a strong limit on this, *disfavouring* DM interpretations of the PAMELA/AMS-02 anomaly

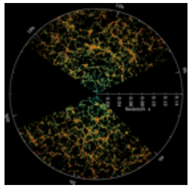
What is the world made of?

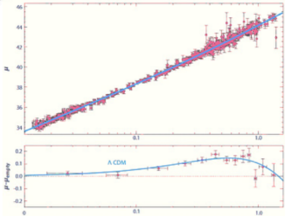
Mainly geometrical evidence:
$\Lambda \sim O(H_0^2)$, $H_0 \sim 10^{-42}$ GeV
… **dark energy** is *inferred* from the
'cosmic sum rule': $\Omega_m + \Omega_k + \Omega_\Lambda = 1$
(*assuming* a homogeneous universe)

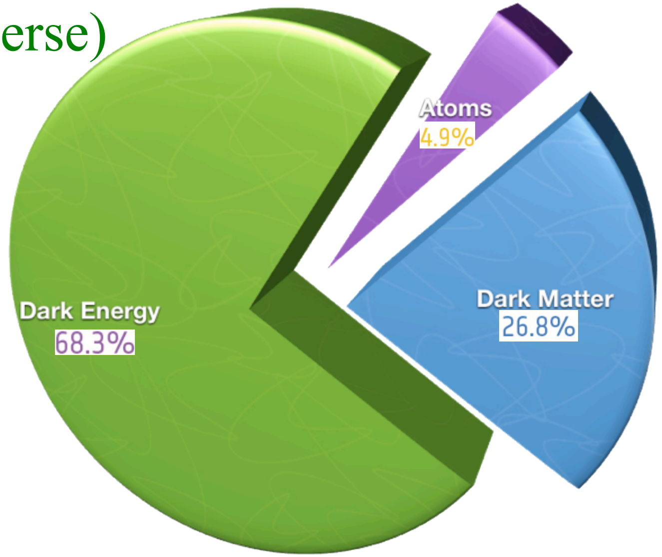


Baryons
(but *no*
anti-baryons)

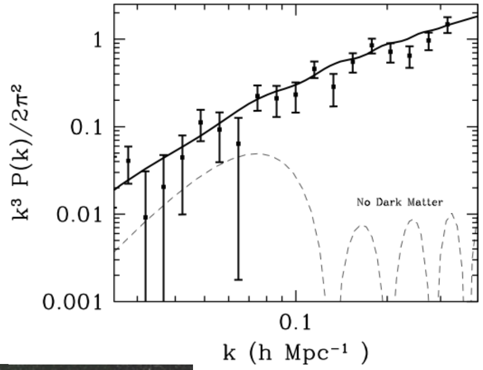




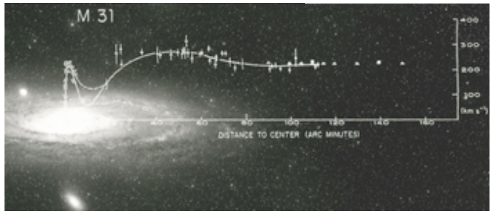


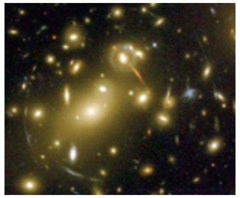


Both geometrical *and*
dynamical evidence for
dark matter (*if* GR valid)



Both the baryon asymmetry and dark matter *require*
new physics beyond the
Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ Model
… dark energy is even more mysterious
(but still lacks compelling *dynamical* evidence)

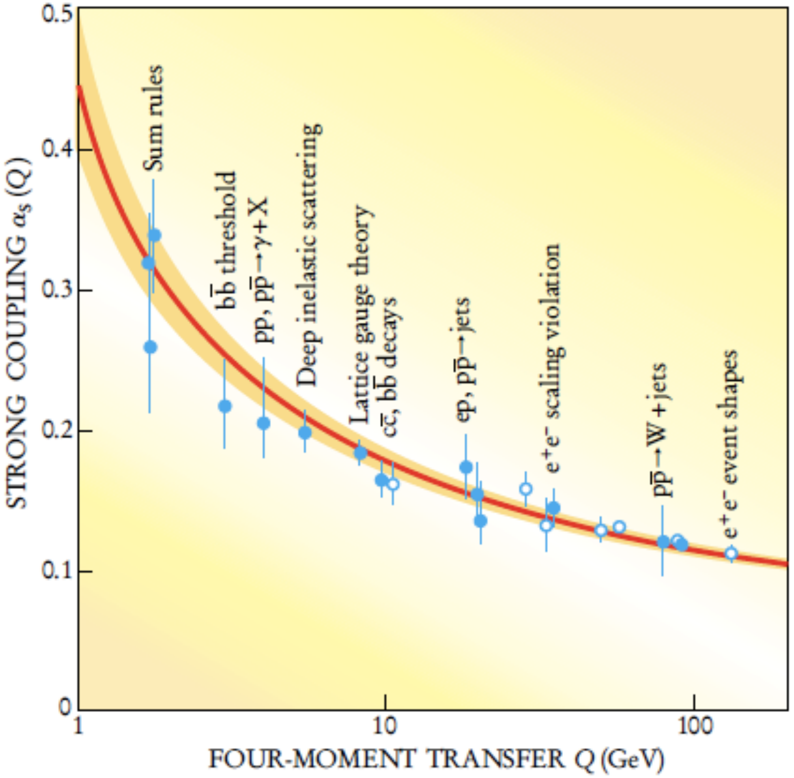


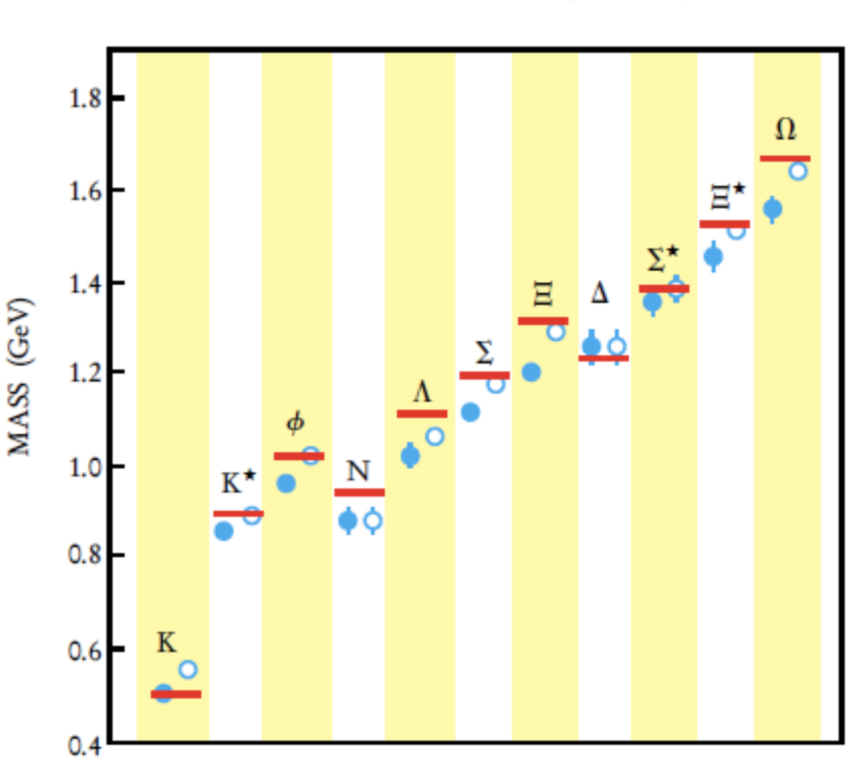


What *should* the world be made of?

Mass scale	Particle	Symmetry/ Quantum #	Stability	Production	Abundance
Λ_{QCD}	Nucleons	Baryon number	$\tau > 10^{33}$ yr (dim-6 OK)	‘freeze-out’ from thermal equilibrium	$\Omega_B \sim 10^{-10}$ *cf.* observed $\Omega_B \sim 0.05$

We have a good theory for why baryons are massive and (cosmologically) stable





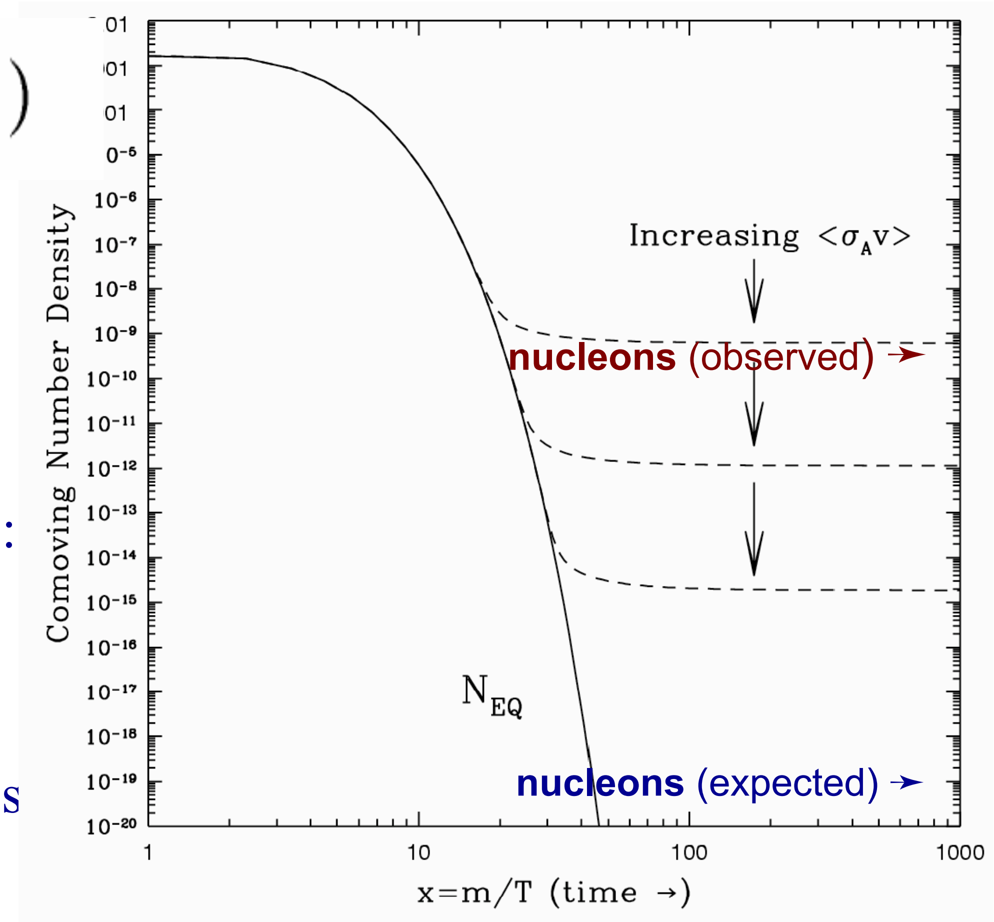
Courtesy: Frank Wilczek, *Physics Today*

However, in the standard cosmology ~none should be left-over from the Big Bang!

What is the expected relic abundance of baryons?

$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\mathrm{T}}^2)$$

Chemical equilibrium is maintained as long as annihilation rate exceeds the Hubble expansion rate



'Freeze-out' occurs when annihilation rate:

$$\Gamma = n\sigma v \sim m_N^{3/2} T^{3/2} \mathrm{e}^{-m_N/T} \frac{1}{m_\pi^2}$$

becomes comparable to the expansion rate

$$H \sim \frac{\sqrt{g}T^2}{M_{\mathrm{P}}}$$ where g is # relativistic species

i.e. 'freeze-out' occurs at $T \sim m_{\mathrm{N}}/45$, with: $$\frac{n_N}{n_\gamma} = \frac{n_{\bar{N}}}{n_\gamma} \sim 10^{-19}$$

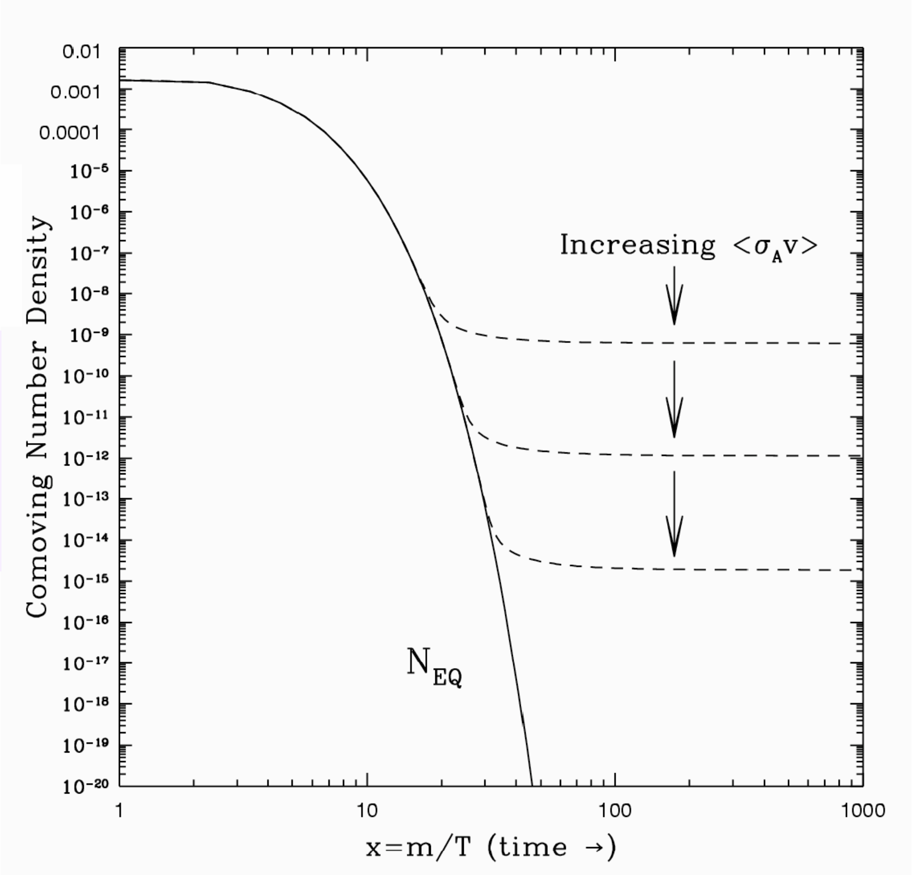
However the observed ratio is 10^9 times bigger for baryons, and there are no antibaryons, so we must invoke an **initial asymmetry**: $$\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$$

(Note: $\Omega_{\mathrm{B}}/\Omega_{\mathrm{DM}} \sim 1/6$)

Thermal relics

$$\dot{n} + 3Hn = -\langle\sigma v\rangle(n^2 - n_{\rm T}^2)$$

Chemical equilibrium is maintained as long as the annihilation rate exceeds the Hubble expansion rate



‘Freeze-out’ can occur either when the annihilating particles are:

- Relativistic: $n \sim n_\gamma$
- Non-relativistic: $n \sim n_\gamma \mathrm{e}^{-m/T}$

Example 1 : $\sum \Omega_\nu h^2 \simeq m_{\nu_i}/93\text{eV}$

➛ how might this mass scale arise (e.g. few keV sterile neutrinos)?

Example 2 : $\Omega_\chi h^2 \simeq \dfrac{3\times10^{-27}\text{cm}^3\text{s}^{-1}}{\langle\sigma_{\rm ann}v\rangle_{T=T_{\rm f}}}$

➛ natural DM abundance for Fermi scale mass/coupling (“WIMP miracle”)

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

$$+M^4 + M^2\Phi^2$$

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

hierarchy problem

super-renormalisable

vacuum energy problem

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

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

renormalisable

$$\boxed{+\theta_{\mathrm{QCD}}F\tilde{F}}$$ → axion?

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

non-renormalisable

neutrino mass

proton decay, FCNC …

New physics beyond the SM ⇒ non-renormalisable operators suppressed by M^n which decouple as $M \to M_P$
… so neutrino mass is small, proton decay is slow → **baryon asymmetry** from ‘leptogenesis’?

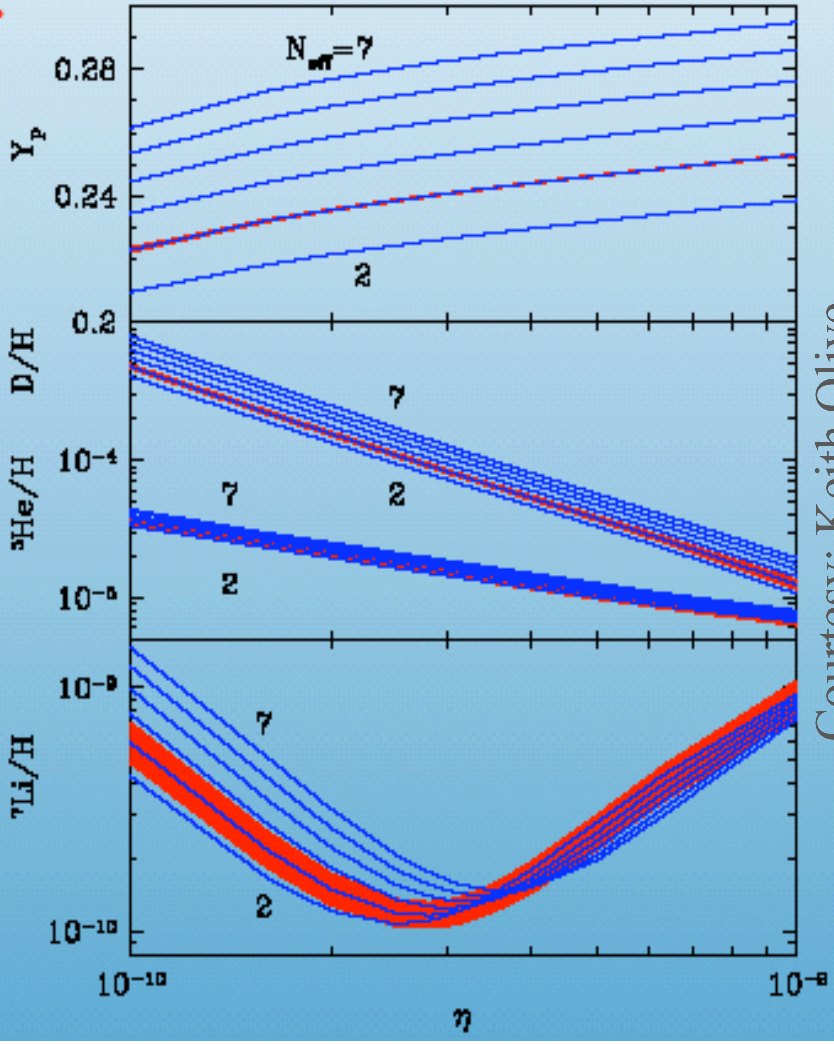
But as M is raised, the effects of the super-renormalisable operators are *exacerbated*
One solution for Higgs mass divergence → ’softly broken’ *supersymmetry* at O(TeV)
… or the Higgs could be *composite* – a pseudo Nambu-Goldstone boson

New TeV-scale physics provides a natural candidate for **dark matter** – e.g. the lightest supersymmetric particle (or techni-baryon or Kaluza-Klein state …)
But there are other possibilities too (axion, sterile neutrino, asymmetric dark matter …)

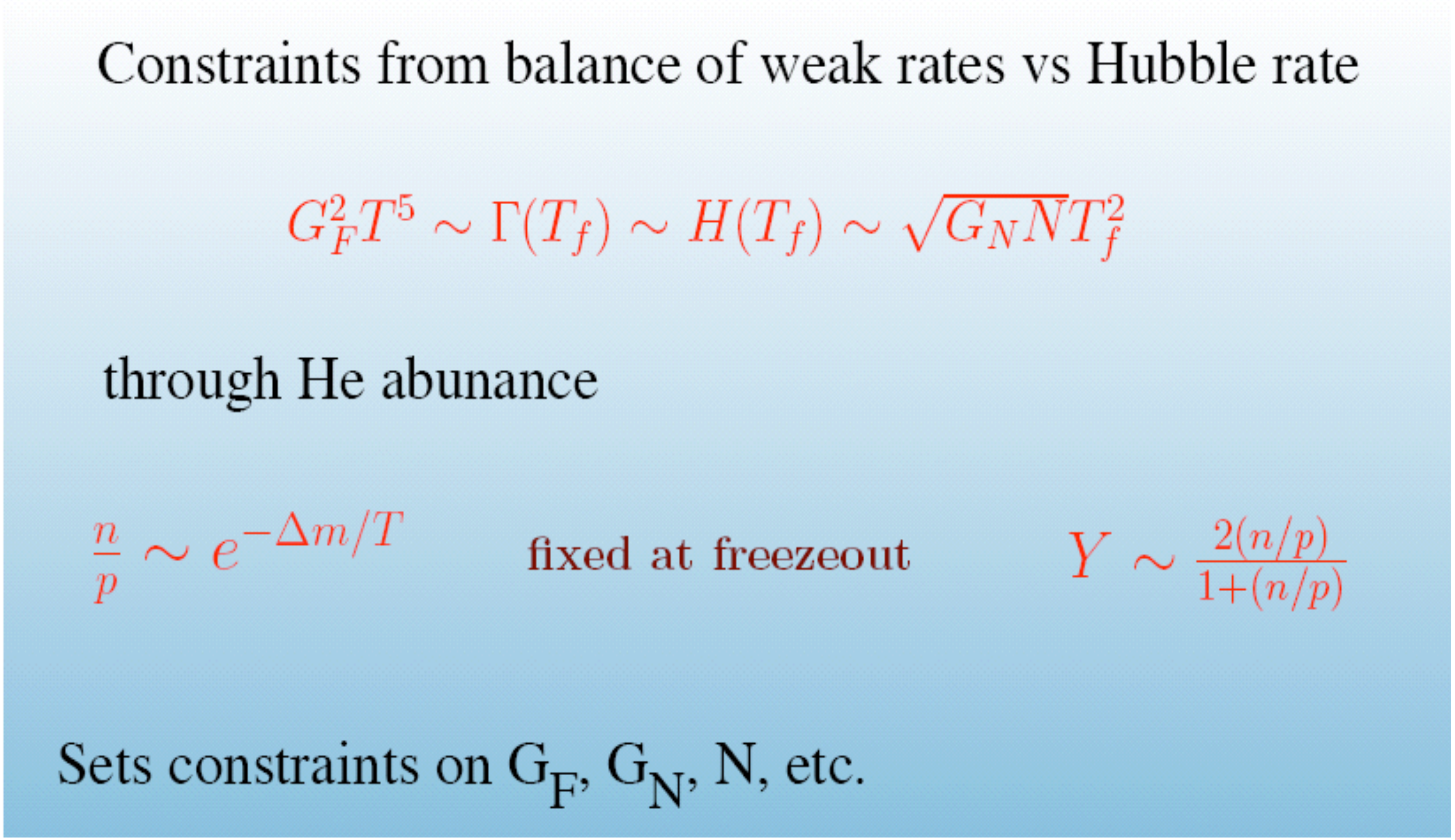
But the ‘cosmological constant’ is $>10^{60}$ times higher than the maximum amount of **dark energy** tolerable today … we do *not* understand how the SM couples to gravity!

Limits on Particle Properties

- BBN Concordance rests on balance between interaction rates and expansion rate.
- Allows one to set constraints on:
  - Particle Types
  - Particle Interactions
  - Particle Masses
  - Fundamental Parameters



Courtesy: Keith Olive



Constraints from balance of weak rates vs Hubble rate

$$G_F^2 T^5 \sim \Gamma(T_f) \sim H(T_f) \sim \sqrt{G_N N} T_f^2$$

through He abunance

$\frac{n}{p} \sim e^{-\Delta m/T}$ fixed at freezeout $Y \sim \frac{2(n/p)}{1+(n/p)}$

Sets constraints on G_F, G_N, N, etc.

Note *n-p* mass difference is sensitive to both em and strong interactions, hence ^{4}He abundance is *exponentially* sensitive to *all* coupling strengths

Conversely obtain bound of less than few % on *any* additional contribution to energy density driving expansion e.g. gravitational waves, `dark radiation', new particles …

E.g. rule out $\Lambda \sim H^2$ (since this just corresponds to a 'renormalisation' of G_N)

"Neutrino counting"

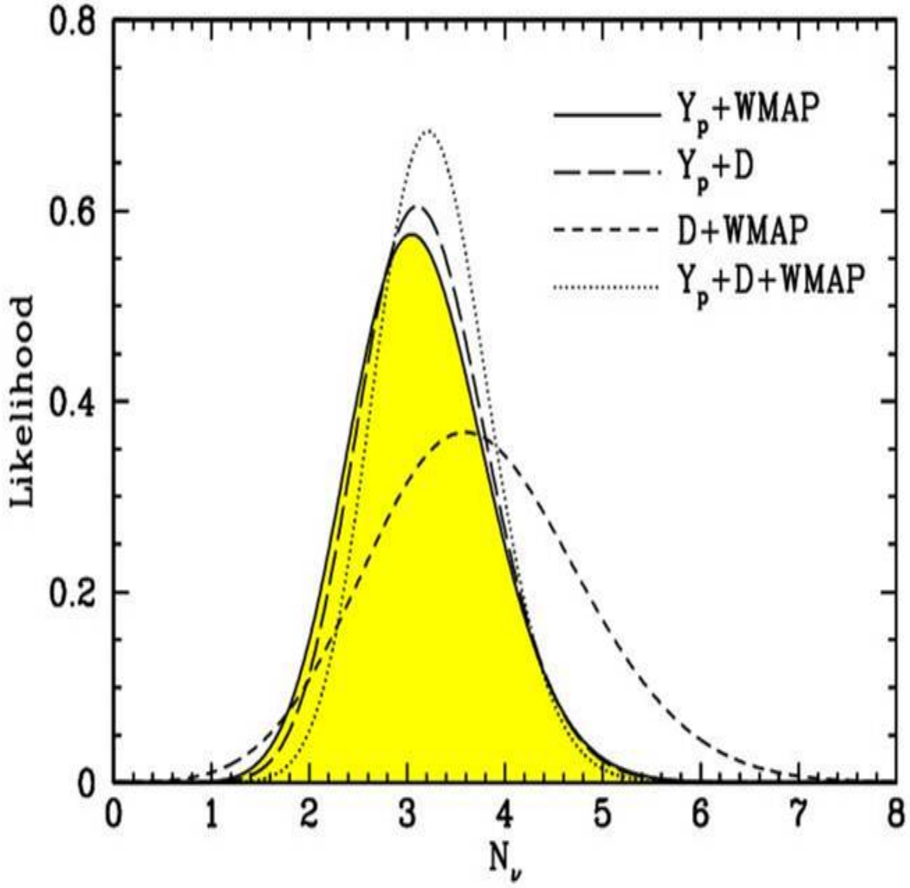
Light element abundances are sensitive to expansion history during BBN

$$H^2 \sim G\rho_{\rm rel}$$

⇒ observed values constrain the relativistic energy density at BBN

$$\rho_{\rm rel} \equiv \rho_{\rm EM} + N_{\nu,\rm eff}\,\rho_{\nu\bar{\nu}}$$

(Hoyle & Taylor 1964, Shvartsman 1969, Steigman, Schramm & Gunn 1977, …)



Cyburt, Fields, Olive, Skillman, AP 23:313,2005

Pre-CMB:

^{4}He as probe, other elements give η

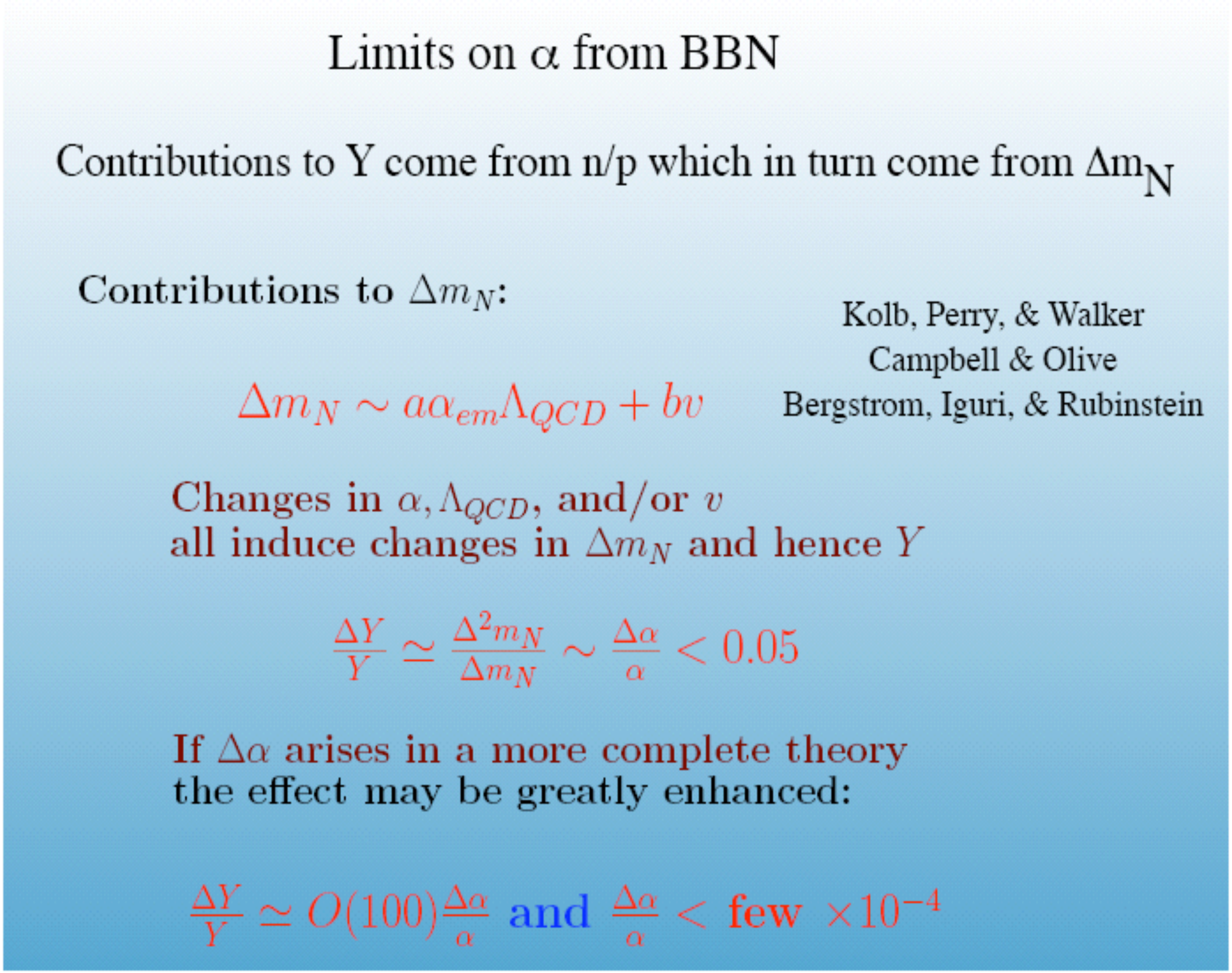
With η from CMB:

All abundances can be used (*assuming* that η did not change between 1 s and 10^5 yr)

$$N_\nu = 3.28 \pm 0.28$$

(Cooke *et al*, *ApJ* **781**:31,2014)

This constrains sterile neutrinos (and other hypothetical particles) which do *not* couple to the Z^0 … *complementary* to laboratory bounds e.g from LEP



Limits on α from BBN

Contributions to Y come from n/p which in turn come from Δm_N

Contributions to Δm_N:

Kolb, Perry, & Walker
Campbell & Olive
Bergstrom, Iguri, & Rubinstein

$$\Delta m_N \sim a\alpha_{em}\Lambda_{QCD} + bv$$

Changes in α, Λ_{QCD}, and/or v
all induce changes in Δm_N and hence Y

$$\frac{\Delta Y}{Y} \simeq \frac{\Delta^2 m_N}{\Delta m_N} \sim \frac{\Delta\alpha}{\alpha} < 0.05$$

If $\Delta\alpha$ arises in a more complete theory
the effect may be greatly enhanced:

$$\frac{\Delta Y}{Y} \simeq O(100)\frac{\Delta\alpha}{\alpha} \text{ and } \frac{\Delta\alpha}{\alpha} < \text{few } \times 10^{-4}$$

In fundamental theories e.g. string theory, the physical “constants” do vary with time
… but the BBN constraint says that this *must* have stopped before t ~ 0.1 s

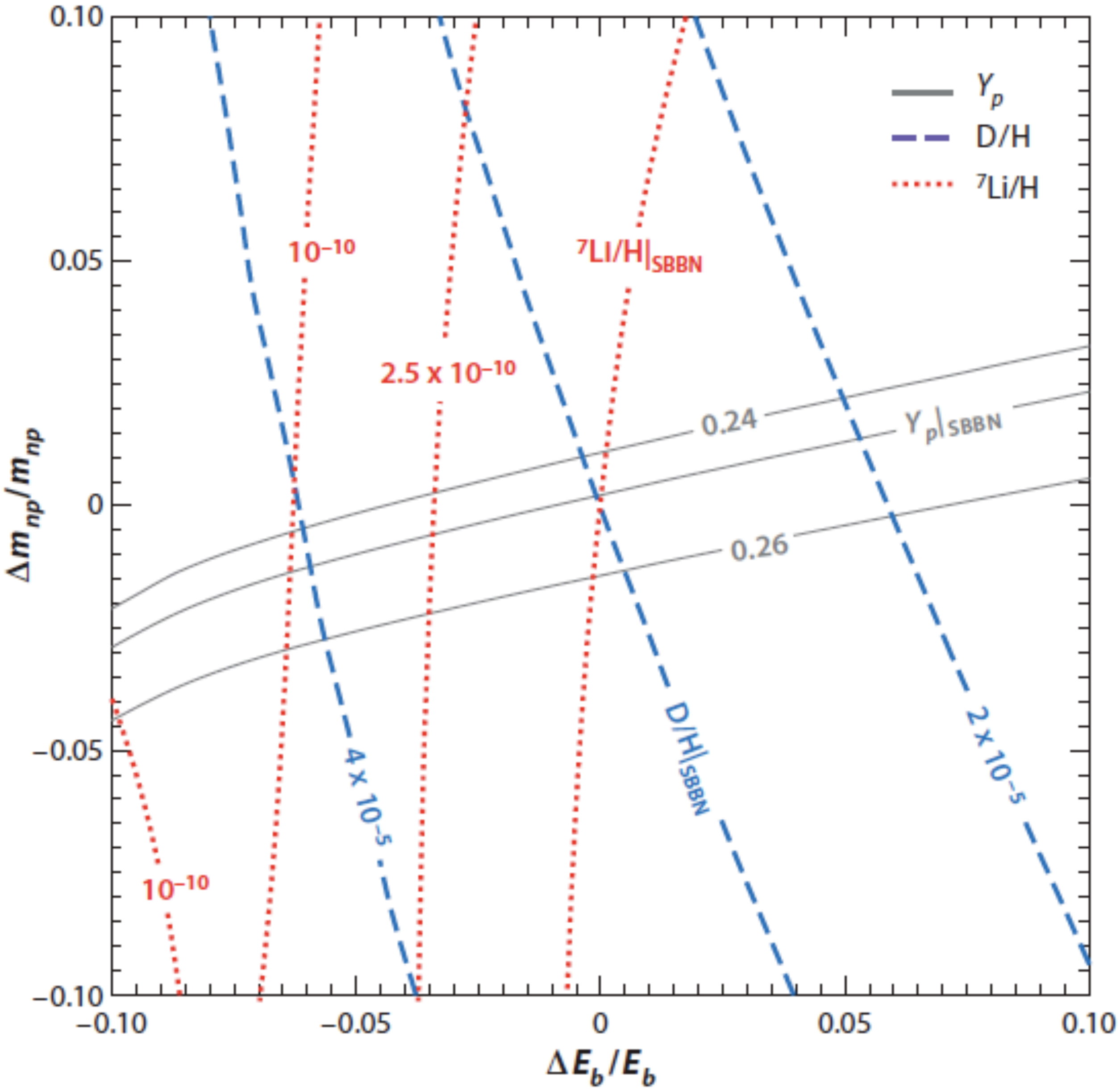


Figure 3

Contours of Y_p, D/H, and ^{7}Li/H are plotted in the parameter space of variable neutron-proton mass difference Δm_{np} and deuteron-binding energy E_d, normalized to their current values. The 5–10% downward change in E_b can significantly reduce the ^{7}Li abundance.

Pospelov & Pradler, ARNPS 60:539,2010

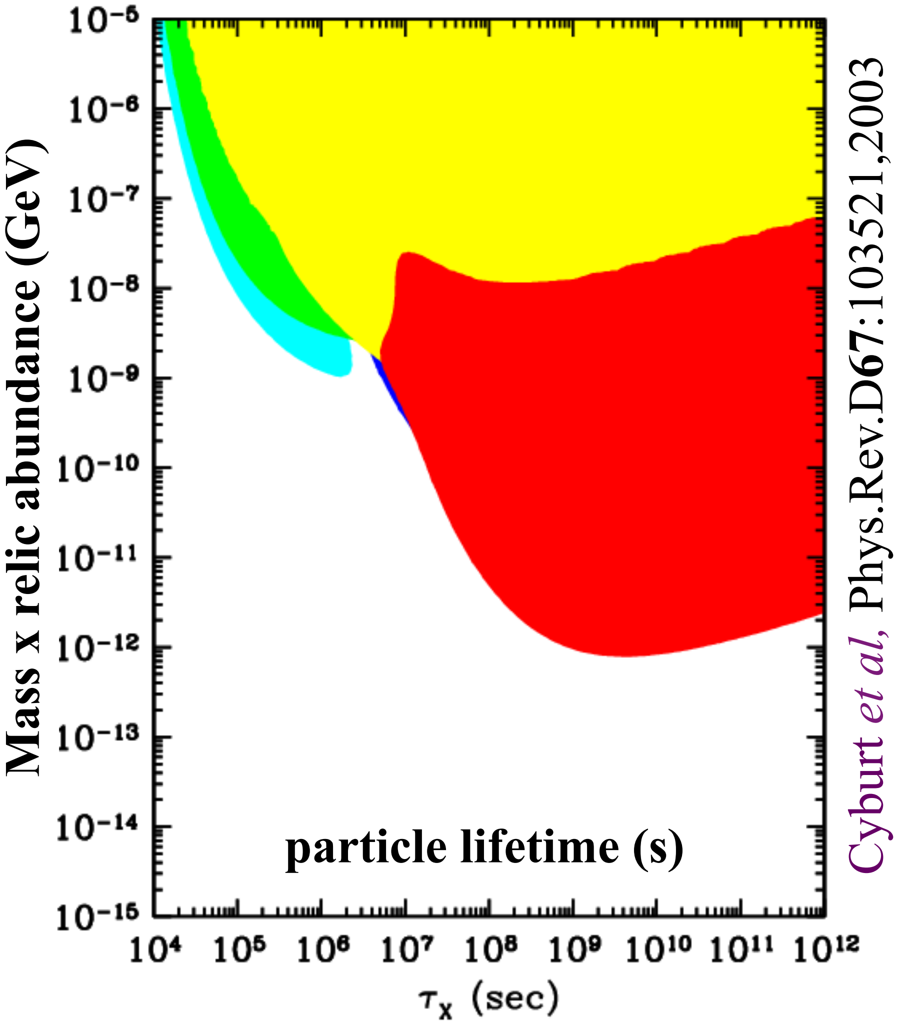
BBN and decaying particles

Extensions of the Standard Model predict new (typically) *unstable* particles, which would have been created (thermally) in the early Universe, e.g. weak scale mass gravitinos in N=1 supergravity

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

(Weinberg 1982; Khlopov & Linde 1983; Ellis, Nanopoulos & Sarkar 1985; Reno & Seckel 1988)

The high energy photons would have photo-dissociated the synthesized elements ⇒ limits on the decaying particle abundance



Cyburt *et al*, Phys.Rev.D67:103521,2003

Since $n_{3/2}/n_{\gamma} \sim T_{\mathrm{reheat}}/M_{P}$, this requires that *highest* temperature reached in our past (after inflation) was $\lesssim 10^{6}$ GeV ⇒ severe constraint on baryogenesis/leptogenesis

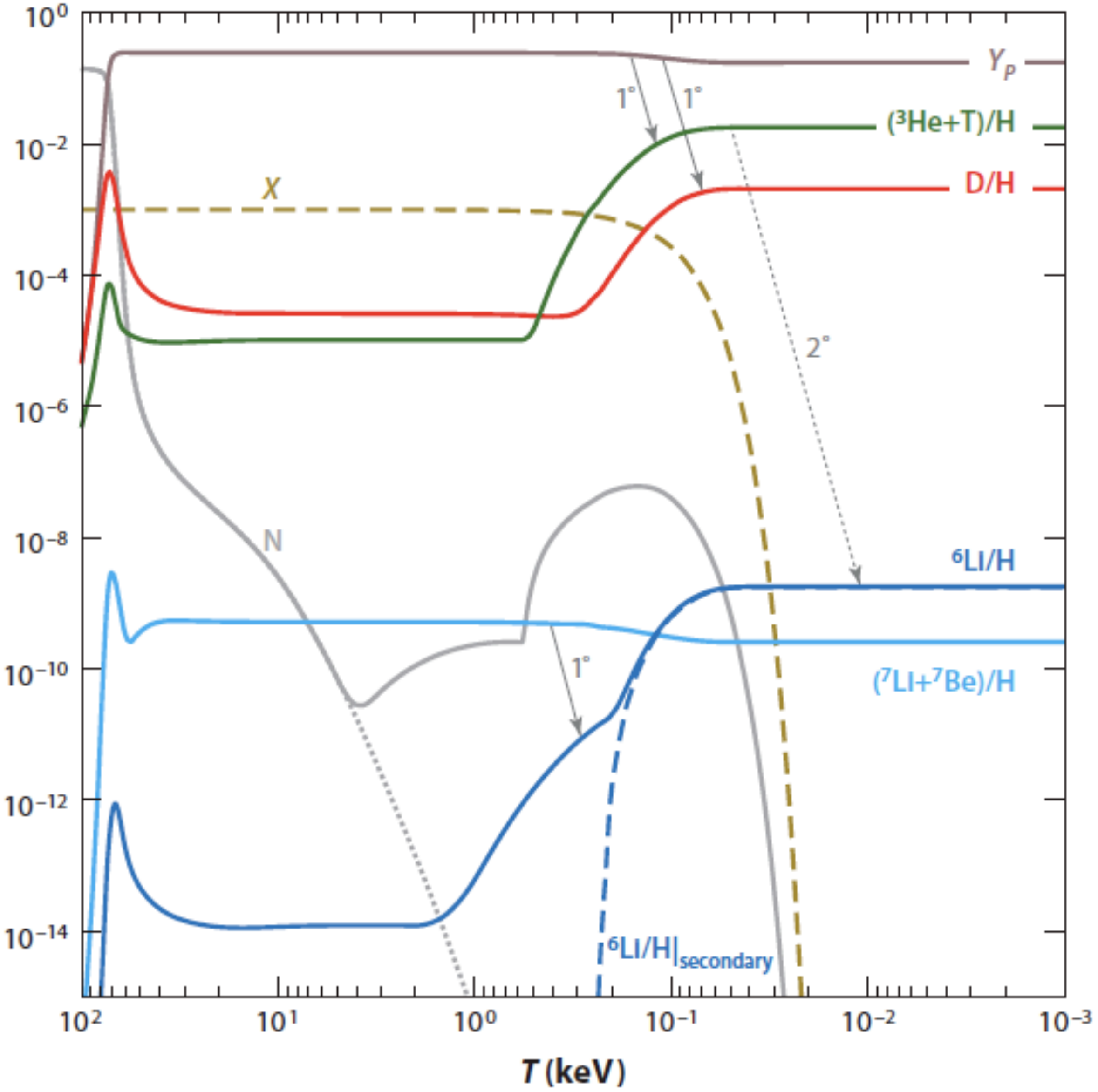


Figure 4

Consequences of late decays of a heavy 1-TeV mass particle X that releases half of its rest mass in the form of electromagnetic energy. The threshold of ^{4}He disintegration is clearly visible below 1 keV. Primary abundance flows are indicated by solid arrows, whereas the dashed arrow indicates the secondary transformation of A = 3 nuclei into ^{6}Li. The model is excluded by the overproduction of D, ^{3}He, and ^{6}Li.

Pospelov & Pradler, ARNPS **60**:539,2010

Is the concordance between the theory and observations cracking up?

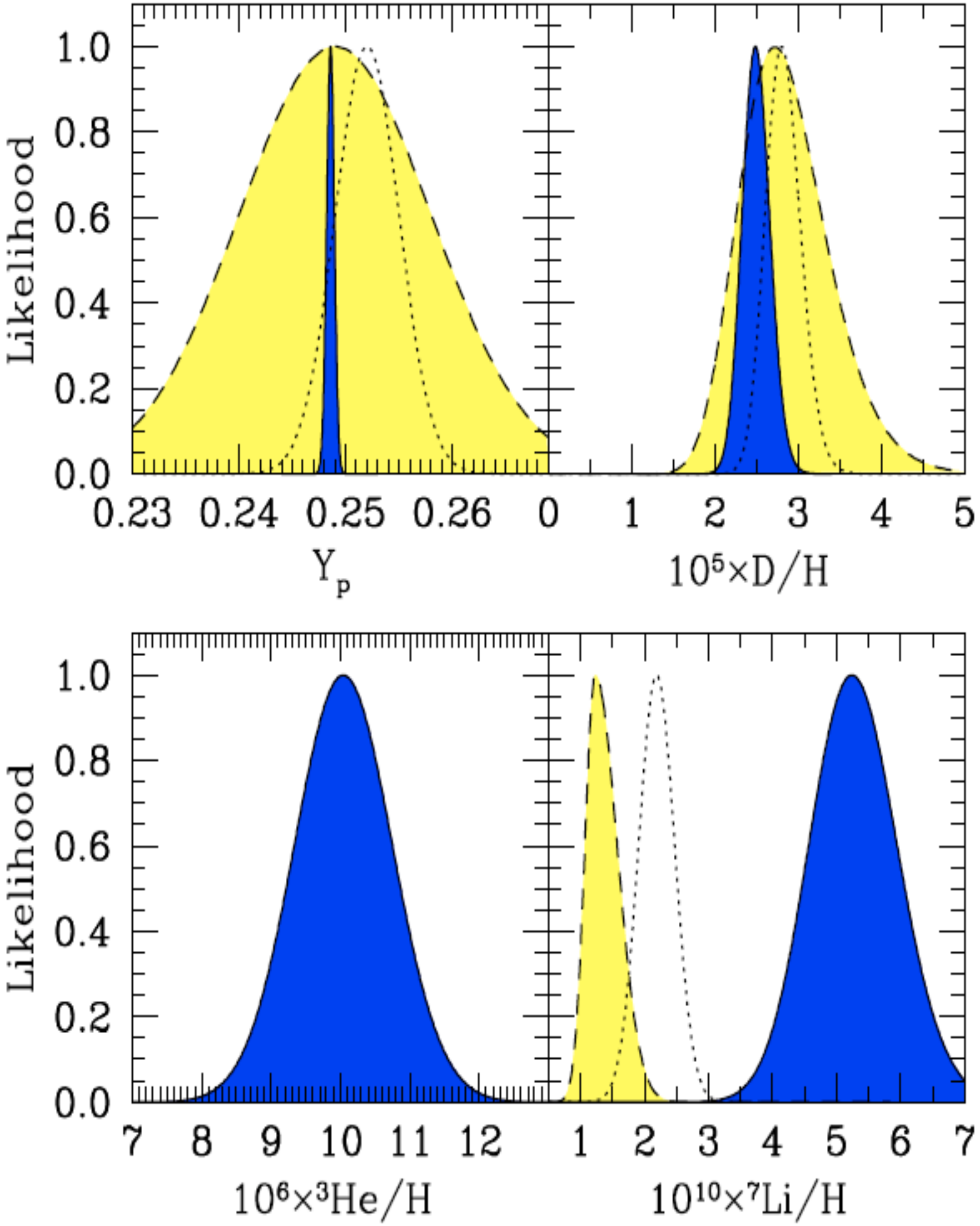
Predicted BBN abundances with WMAP determination of η_{CMB}(blue) compared with observations (yellow)

- ➢ D agreement excellent, ^{4}He also OK
- ➢ But ^{7}Li is *discrepant*

- systematic errors in observations?

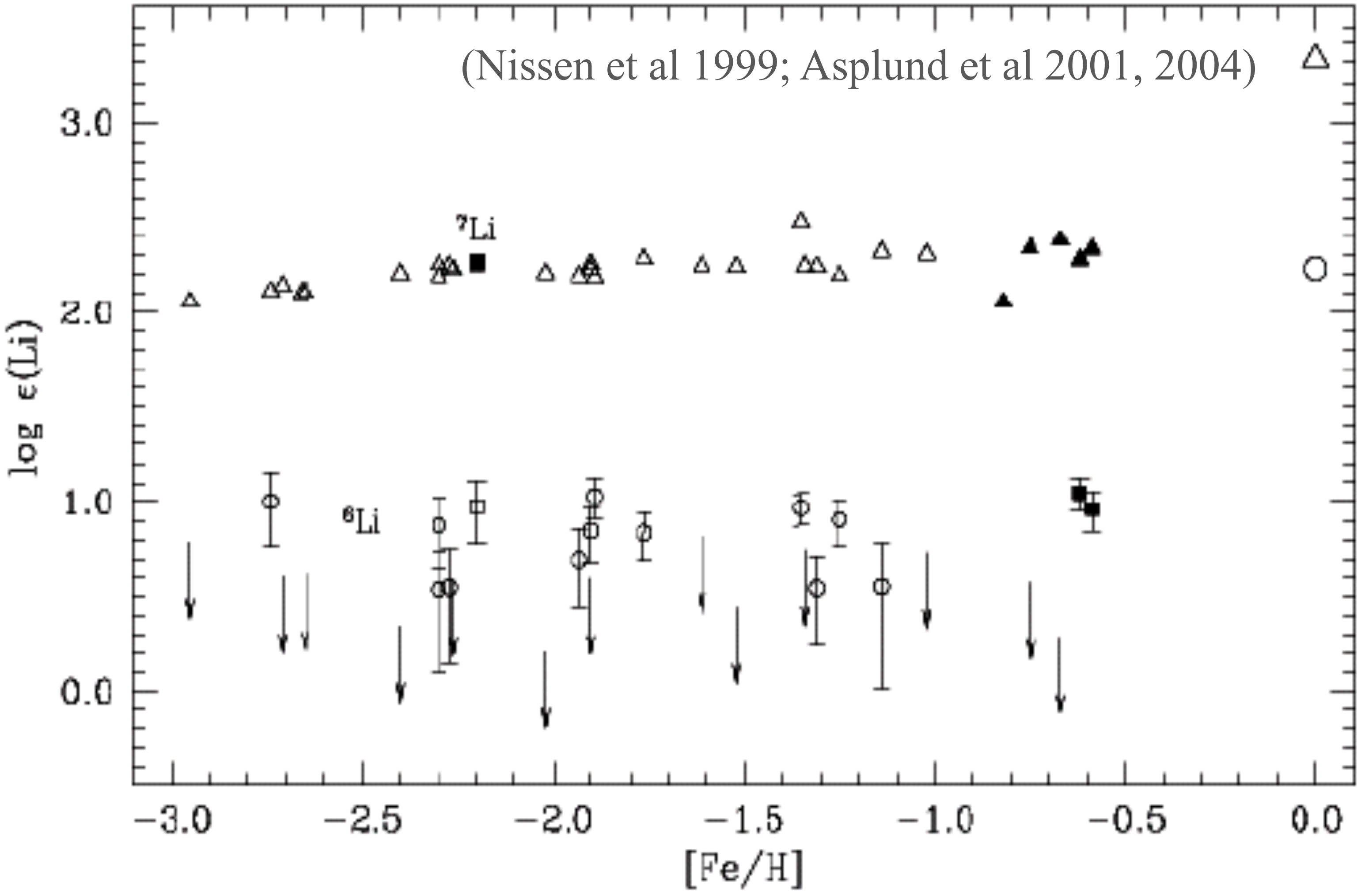
- theoretical uncertainties?

- new physics (e.g. decaying relic particles)? → this has added motivatio from the observation that ^{6}Li has also been observed ‑ with an abundance > 10^4 times higher than expected!

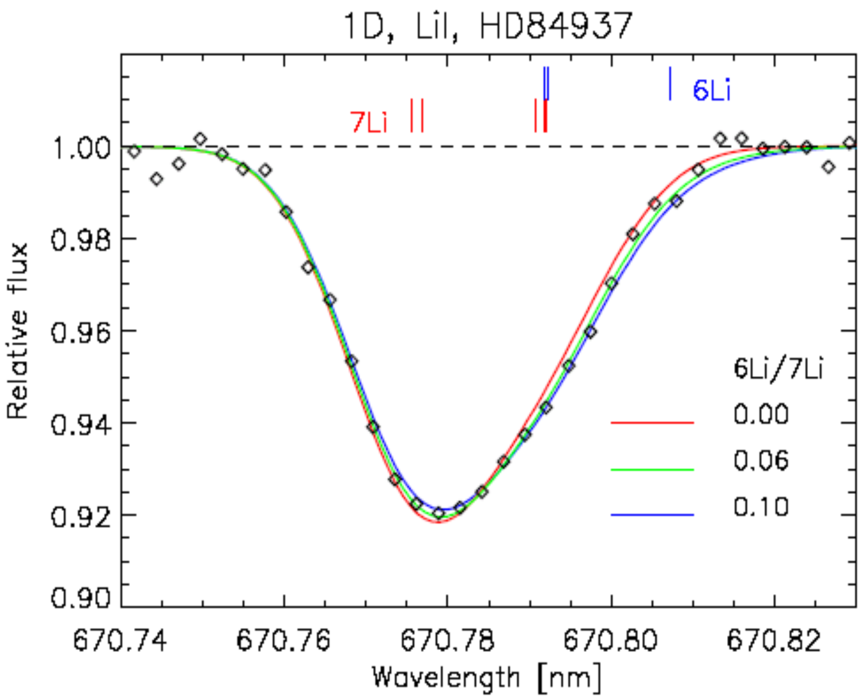


Cyburt, Fields & Olive, JCAP **11**:012,2008

A primordial ‘plateau’ in ^{6}Li is claimed to have been detected with ^{6}Li/^{7}Li ~ 0.1 (*cf.* standard expectation ^{6}Li/^{7}Li ~ 10^{-5})



Coupled with the fact that the ^{7}Li abundance is ~3 times *smaller* than expected, this has refocussed interest on **non-standard BBN**



The Li I 6707 Å resonance doublet in HD 84937 from Smith et al. (1993). The wavelengths of the ^{7}Li and ^{6}Li re indicated at the top of the figure. Synthetic profiles for three ^{6}Li/^{7}Li ratios are shown – courtesy of Martin Asplund.

However the 'detection' of ^{6}Li is based on fits to the line shape … need more data to establish the reality of a '^{6}Li plateau'

Also stars in which ^{6}Li is detected are close to the main-sequence turn-off in the H-R diagram

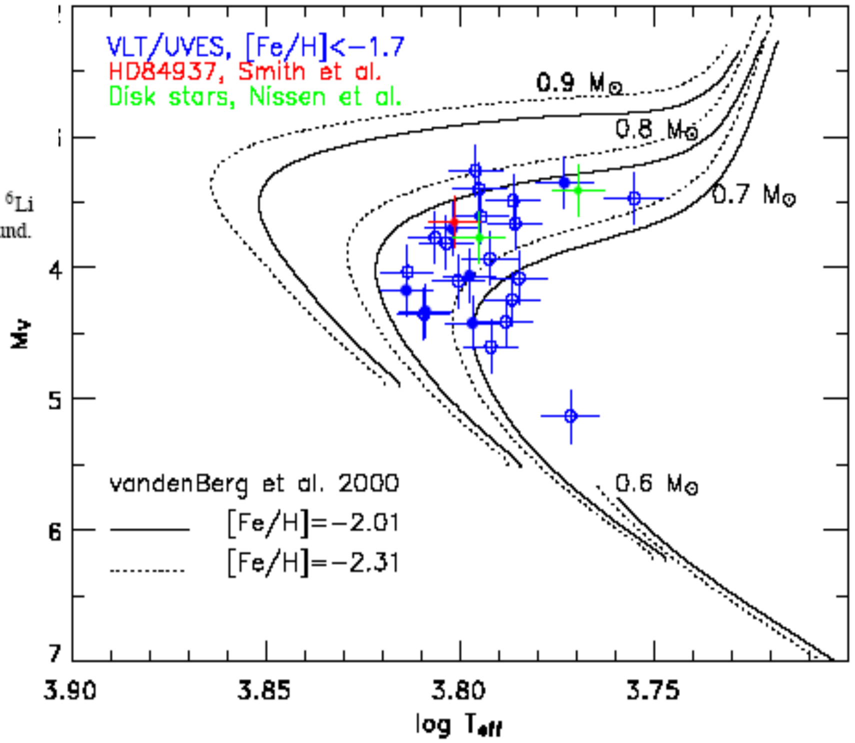
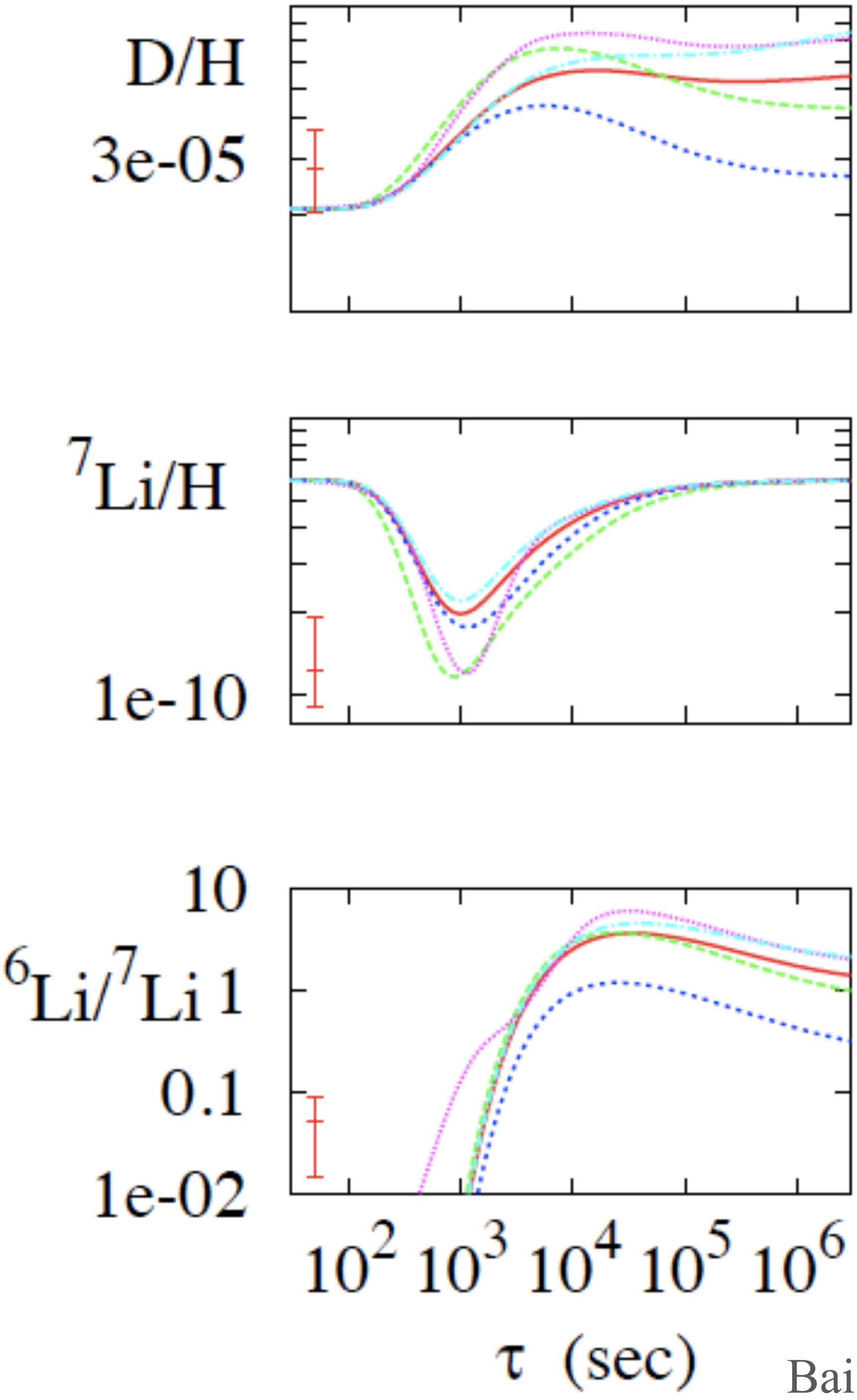


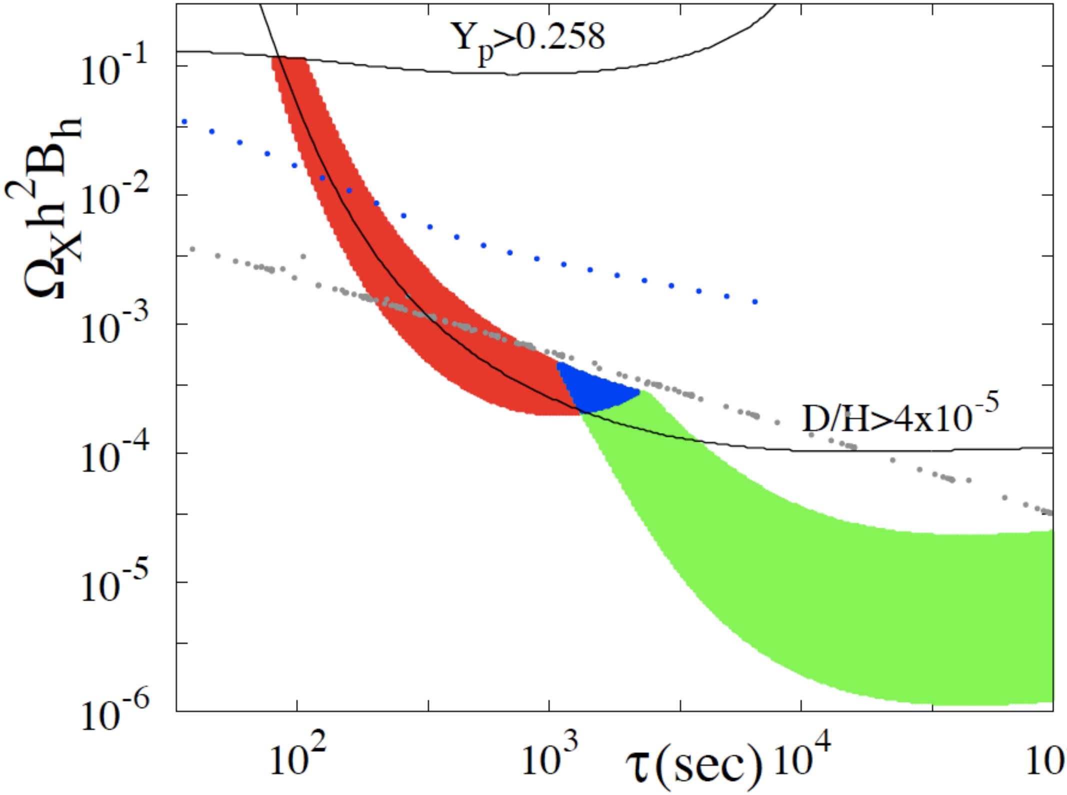
FIGURE 4. The Hertzsprung-Russell diagram for stars from Figure 3 with [Fe/H] < −1.7. Filled symbols denote stars with a detection of ^{6}Li according to the key in the top left corner of the figure. Evolutionary tracks for the indicated stellar masses and metallicities are from VandenBerg et al. (2000).

Lambert (2005)



May be possible to solve *both* ‘lithium problems’ with relic decaying particle having suitable abundance/lifetime

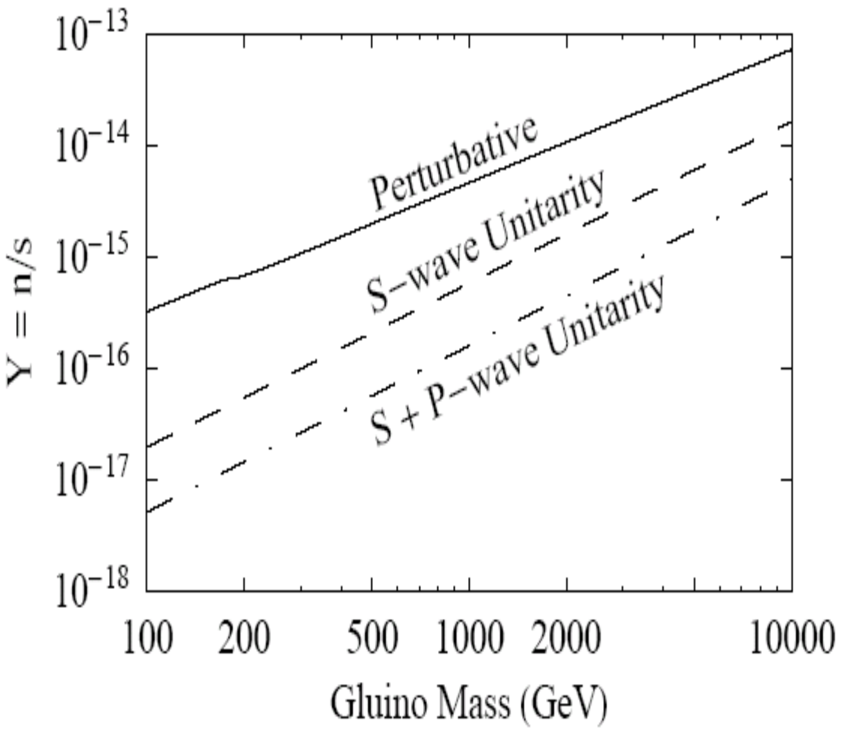
e.g. gluino in split supersymmetry, supersymmetric stau Next-to-LSP (with gravitino LSP), …

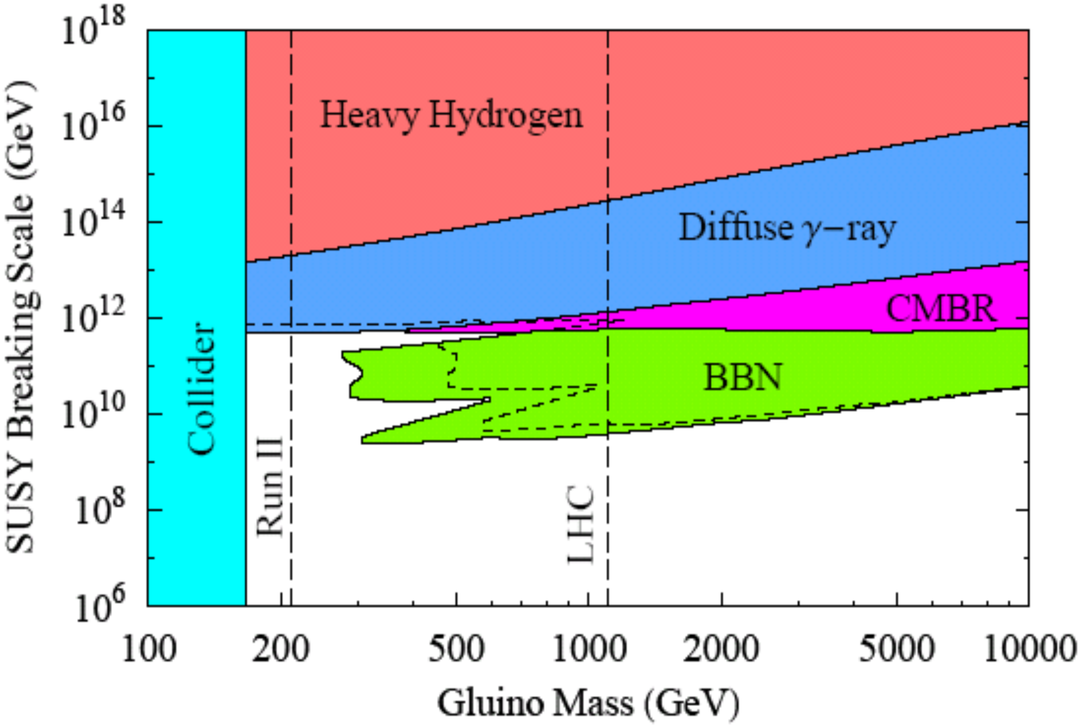


Bailly, Jedamzik & Moultaka, Phys.Rev.D80:063509,2009

Gluino in ‘split’ supersymmetry

If mass scale of SUSY scalar superpartners is raised well above a TeV (to evade various problems with weak scale SUSY breaking), then predict *long-lived* gluinos





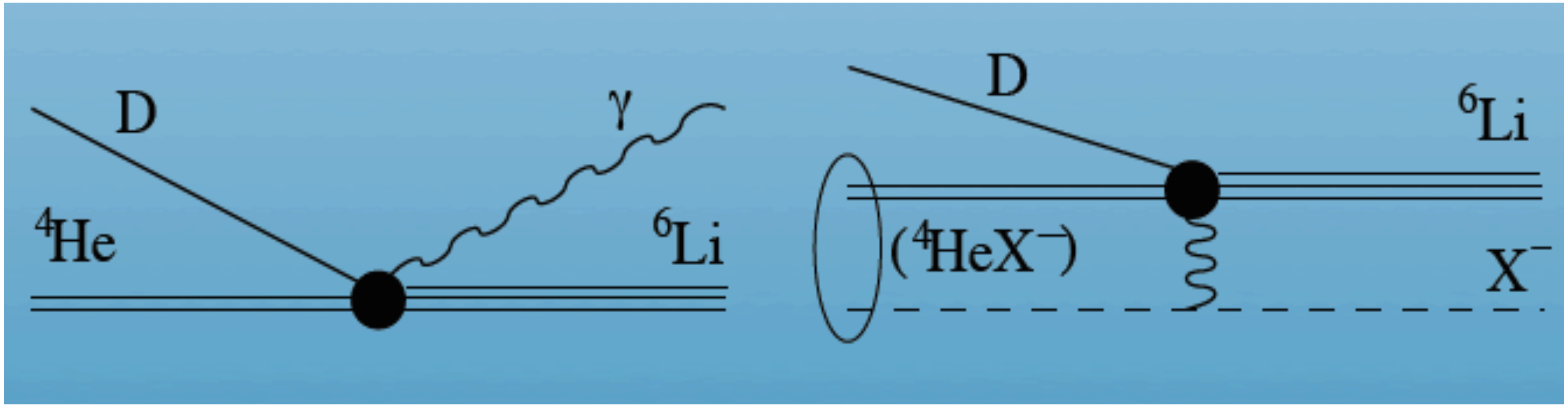
A small number of these would survive annihilation in the early universe and decay during nucleosynthesis → stringent bound from overproduction of D + ^{3}He

This would require supersymmetry breaking scale to be < 10^{10} GeV

Arvinataki *et al*, Phys.Rev. D72 (2005) 075011

There may also be new *charged* quasi-stable relic particles in Nature which would form **bound states** with ^{4}He

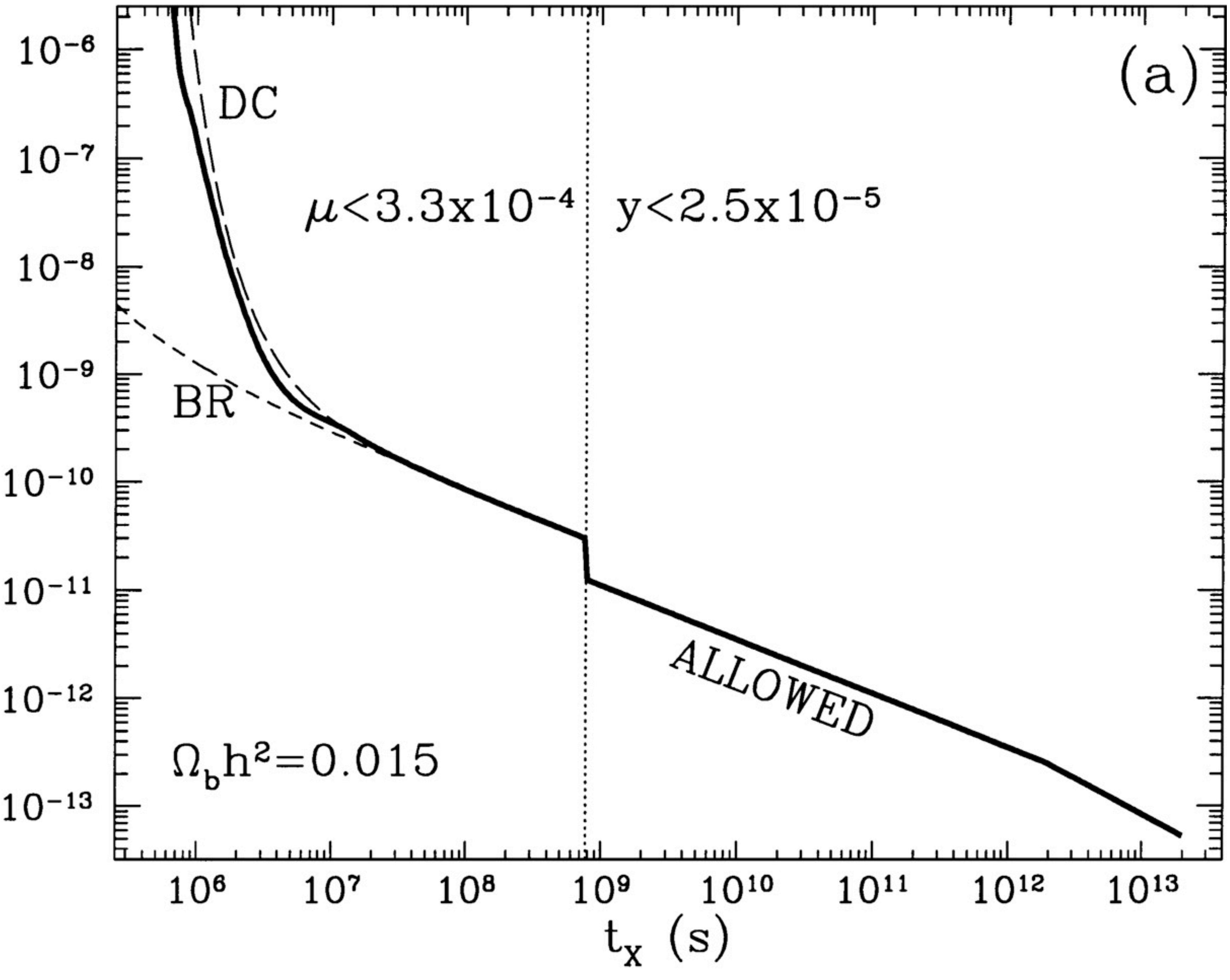
Although the ^{4}He (D, γ) ^{6}Li reaction is normally highly suppressed, this is *not* so for the bound state …



Pospelov, PRL **98**:231301,2007

Thus the lithium anomaly may be due to charged supersymmetric particles (e.g. stau) which can catalyse relevant nuclear reactions … if so these could be seen soon at the LHC!

CMB constraint on particles decaying/annihilating into em radiation



Ellis *et al*, NP B373:399,1992, Hu & Silk, PR D48:485,1993

Addressing the ‘big questions’

We have today a ‘standard’ model of both particle physics and cosmology which allows us to extrapolate back from the present day to the very first moments following the Big Bang

While successful in accounting for a wide range of observations, this has raised a new set of more fundamental questions concerning the universe

◆ *The origin of the baryon asymmetry*
◆ *The nature and origin of dark matter*
◆ *The origin of the primordial density perturbations that seeded structure*
◆ *The nature and origin of dark energy*

\+

- The initial singularity problem
- The cosmological constant problem
- The origin of space-time,
- …