Recap : local thermodynamical equilibrium : $\Gamma > H$

interaction rate (Γ)   expansion rate (H)

Universe expands : $\Gamma \downarrow$ faster than $H \downarrow$ (e.g. $\Gamma \sim G_F^2 T^5$ vs. $H \propto T^2 g_*$) : $\Rightarrow T \propto \sqrt[3]{g}$

freeze-out at $\Gamma = H$ e.g. neutrinos freeze-out at $T \simeq 0.75$ MeV (hot!)

$T_\nu^{\text{now}} = \sqrt[3]{\frac{11}{4}}\, T_\gamma^{\text{now}} = 1.9\,K$; $n_\nu = 2 \cdot 3 \int \frac{d^3p}{(2\pi)^3} \Phi_F(\vec{p}, T_\nu^{\text{now}}) = 336\ \text{cm}^{-3}$

note: E, T scale with z identically $\Rightarrow \Phi_F = \frac{1}{e^{-E/T}+1}$ stays

For non-relativistic particles : $\rho = n \cdot m$

$$\Rightarrow \Omega_\nu = \frac{\rho_\nu}{\rho_{cr}} = \frac{\sum m_i\, n_\nu}{\rho_{cr}} = \frac{\sum m_i\, n_\nu}{3H^2/8\pi G_N} \Rightarrow \Omega_\nu h^2 \simeq \frac{\sum m_i}{94\ eV}$$

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i) neutrinos non-relativistic: $\rho = 3 n_\nu m_\nu \Rightarrow \Omega_\nu h^2 = \frac{\sum m_i}{94\,eV}$

$$\downarrow$$

$$f_F = \frac{1}{e^{E/T}+1} \rightarrow e^{-m/T}$$

if $\nu = DM$: $\Omega_\nu h^2 \simeq 0.25 \Rightarrow$ $\sum m_i \simeq 25\,eV$ (BUT: ν would be hot dark matter, relativistic when freezing out)

$m_3 \simeq \sqrt{\Delta m_A^2}$; $m_2 = \sqrt{\Delta m_\odot^2}$, $m_1 = 0$ $\qquad \sum m_i = 0.06\,eV$

$m_2 \simeq m_1 = \sqrt{\Delta m_A^2}$; $m_3 = 0$ $\qquad \sum m_i = 0.1\,eV$

typical limits on $\sum m_\nu$ nowadays $\lesssim 0.2\,eV$

cf. to KATRIN: $m_\nu = \sqrt{\sum |U_{ei}|^2 m_i^2} \leq 0.8\,eV$
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corresponds to $\sum m_i \simeq 2.4\,eV$...

$\leftrightarrow$ Cosmological limits related to structure formation and Cosmic Microwave Background

initial perturbations (overdensities) as seeds of structure (galaxies, clusters, ..)

Neutrinos are hot (= relativistic), escape potential wells, level energy over/under-densities

Slow down growth of gravitational potential wells on scales $\lambda << \lambda_{FS}$

$$\lambda_{FS} \sim \left(\frac{eV}{m_\nu}\right) MPc$$

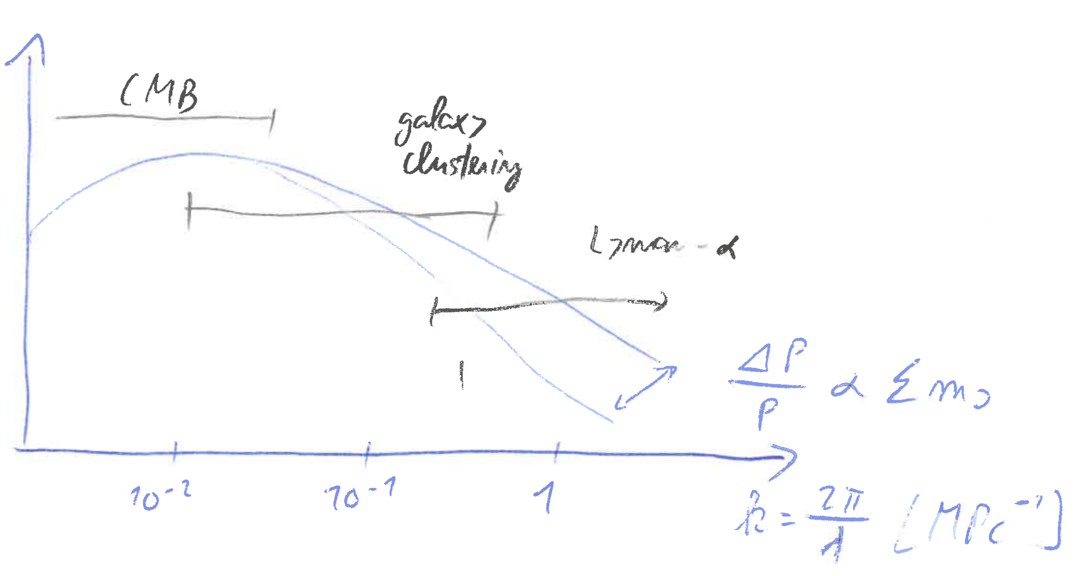
$\leftrightarrow$ the closer scale to MPc, the larger the effect

" power spectrum "

$\updownarrow$

statistically treated Fourier trafo of density fluctuations

$$\delta = \frac{\rho(t,\vec{x}) - \langle\rho(t)\rangle}{\langle\rho(t)\rangle}$$



„Cosmological SM": ΛCDM : 6 parameters : H_0 , $h^2 \Omega_{Baryon}$, $h^2 \Omega_{Matter}$, τ , $P_{in}(k) = A k^{n_s}$
($k = 0$, $w_{DE} = -1$)

optical depth for scattering of CMB with ionized e^-

add Σm_ν to fits of many (many!) observables.

#) CMB: > relativistic, not a good probe; shift in matter-radiation equality, degenerate to many other effects

#) CMB lensing
#) galaxy clustering
#) cluster counts
#) Lyman-α

→ distribution of matter along line-of-sights at different times
the smaller the scales, the larger effect of m_ν; but the more systematics (↔ isotropy + homogenity...)

strongest limits: $\Sigma m_\nu \lesssim 0.1\, eV$

BUT: degeneracies, problems, not a lab measurement ↔ complementarity

simplest models: by next 10 years, see effect of Σm_ν in upcoming surveys!

Also important: $N_{eff} \leftrightarrow$ BBN Big Bang Nucleosynthesis (1s … 3 min, production of D, ^3He, ^4He, ^7Li)

① $T \simeq GeV \ldots 10^2$ MeV $u, d, \ldots, g \rightarrow p, n$

② $\bar{\nu}_e \, p \leftrightarrow e^+ n$

$\nu_e \, n \leftrightarrow e^- p$

$n \leftrightarrow p \, e^- \bar{\nu}_e$

freeze out at $T_f \simeq 0.75$ MeV

$$\left(\frac{n}{p}\right)_0 = \exp\left\{\frac{-\Delta m}{T_f}\right\} \simeq \frac{1}{6} \qquad \Delta m = m_n - m_p$$

neutrons decay: $\left(\frac{n}{p}\right) = \left(\frac{n}{p}\right)_0 \exp\left\{-t/\tau\right\} \simeq \frac{1}{7}$ after 3 min (0.2 MeV)

③ $T \simeq 0.2$ MeV: BBN starts $p(n,\gamma)D \equiv n + p \rightarrow \gamma + D$

$E_B = 2.2$ MeV (less than T, but tail of distribution)

(not earlier, because $\frac{n_B}{n_\gamma} \simeq 10^{-10}$)

too many photons…

then complicated nuclear chain starts, producing ^3He, ^4He, ^7Li

most goes in $D + D \rightarrow {^4He} + \gamma$ stops at $A = 5, 8$, too large Coulomb barrier

4 /

mass fraction of ^4He: $Y = \frac{m(^4He)}{m_{Baryon}} = \frac{4 m_p n_{^4He}}{m_p(p+n)} = \frac{4\, n/2}{p+n} = \frac{2\, n/p}{1 + n/p} \simeq \frac{2 \cdot 1/7}{8/7} = \frac{1}{4}$

$T_{fr} \propto \left(\sqrt{g_*}\right)^{1/3}$; $g_* = 2 + \frac{7}{8}\left(4 + 2 \cdot (3 + \Delta N_{eff})\right)$

$\Delta N_{eff} \nearrow$: $T_{fr} \nearrow \Rightarrow \left(\frac{n}{p}\right)_0 = e^{-\Delta m / T_{fr}} \nearrow \Rightarrow \frac{n}{p} \nearrow$

$\Rightarrow Y \nearrow$

$\Rightarrow \Delta N_{eff} \lesssim 0.5$

Why would N_{eff} be $\neq 3$?

→ any hot particle (BSM) would contribute

→ light sterile neutrinos ...

Light sterile neutrinos

Various longstanding hints ...

LSND : 800 MeV p-beam on H_2O target $L = 30\,m$, $E_{\bar\nu_\mu} \simeq 30$ MeV

$$P(\bar\nu_\mu \to \bar\nu_e) \simeq 3 \times 10^{-3} \neq 0 \text{ at } \simeq 4\sigma \Rightarrow \frac{\Delta m^2}{eV^2} \frac{L}{m} \frac{MeV}{E} \sim 1$$

$$\Rightarrow \Delta m^2 = eV^2 \gg \Delta m^2_{21,sol} , \Delta m^2_{31,atm}$$

$$\sin^2 2\theta \simeq 10^{-2} \Rightarrow$$

Also: MiniBoone similar parameters.

+ Reactor Anomaly: Re-analysis of reactor neutrino flux (new data, Treatm, ...)
flux 6% ~~less~~ more than previously thought
$\Rightarrow$ all experiments measured less neutrinos than they should have $\Rightarrow P(\nu_e \to \nu_s)$ compatible with LSND values!

+ GALLEX

We know from LEP that $Z \to \nu\nu$ (invisible Z-width) implies $N_\nu = 3$

$\Rightarrow$ only 3 <u>active</u> neutrinos (with mass $< m_Z/2$)

$\Rightarrow$ the fourth state must be <u>sterile</u> (no isospin, or accompanying charged lepton)

$$\Rightarrow \mathcal{U} = \begin{pmatrix} \mathcal{U}_{e1} & \mathcal{U}_{e2} & \mathcal{U}_{e3} & \mathcal{U}_{e4} \\ \mathcal{U}_{\mu 1} & \mathcal{U}_{\mu 2} & \mathcal{U}_{\mu 3} & \mathcal{U}_{\mu 4} \\ \mathcal{U}_{\tau 1} & \mathcal{U}_{\tau 2} & \mathcal{U}_{\tau 3} & \mathcal{U}_{\tau 4} \\ \mathcal{U}_{s1} & \mathcal{U}_{s2} & \mathcal{U}_{s3} & \mathcal{U}_{s4} \end{pmatrix}$$

would contain 6 mixing angles
3 CP phases (+ 3 for Majorana)

should show up everywhere $\Rightarrow$ many tests in dedicated experiments, plus in other experiments that look for other things ...

In general, <u>not</u> consistent with cosmology (1) $N_{eff} = 4$ 2) $\sum m_\nu \gtrsim \sqrt{\Delta m^2_{41}} \sim eV$)

need extra new physics to address this