Lecture 6: Sterile neutrinos

Motivation for sterile neutrinos:

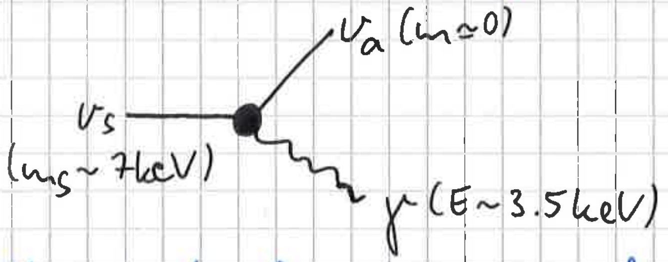
- What is a sterile neutrino?
  ↳ RH-neutrino: $N_R \sim (\underline{1}, \underline{1}, 0) \Rightarrow$ total SM-singlet $\Rightarrow$ "sterile"
  $\Rightarrow$ if the corresponding mass eigenstates are comparatively light (usually $\lesssim$ GeV), they are typically called "sterile neutrinos" (slightly unfortunate trend in the literature, since the value of the mass is in fact not important)
- Why should we need them?
  - neutrino masses may need RH-ν's $\Rightarrow$ could easily be light, as their mass is not connected to EWSB
  - AND: Z-decay does NOT forbid light sterile neutrinos (as well as other requirements such as anomaly cancellations)

Experimental evidence:

- accelerator neutrinos:
  - LSND ($\sim$ 2000): excess of electron neutrinos in $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions
    ↳ this could be interpreted as arising from an additional "fast" oscillation with $\Delta m^2 \sim 1\,\text{eV}^2$
    $\Rightarrow$ may indicate sterile ν's of eV-scale mass
  - similar results by MiniBooNE, but constraints from KARMEN & ICARUS
- reactor anomaly:
  - new calculation of reactor ν-spectrum $\Rightarrow$ flux estimates higher than previously by $\sim 3\%$
    $\Rightarrow$ sterile ν's already discovered?!? (again $\Delta m^2 \gtrsim 1\,\text{eV}^2$)
  - somewhat consistent if a deficit in Ga-based solar ν-experiments is also

interpreted in terms of sterile neutrinos

- BUT: anomalies do not seem to fit together
- in addition: astrophysical indication for an X-ray line signal (BUT: not clear yet!)
  - $\Rightarrow$ IF the signal survives, it could be interpreted as sterile ν decay:



$\Rightarrow$ keV-scale instead of eV

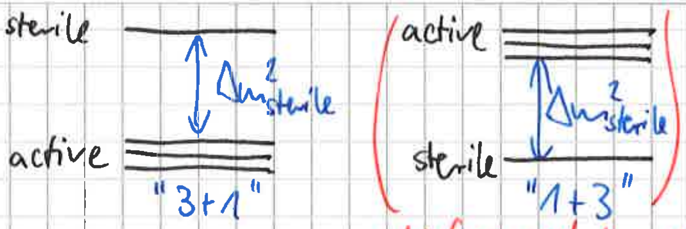
- previously: possible indication for extra species of neutrinos from cosmology ($N_{eff} > 3$)
  - ↳ BUT: seems disproved by newest Planck data (2015 release)

4-neutrino mixing:

- $U_{PMNS} \in \mathbb{C}^{4\times4}$ & unitary:
  - $\mathbb{C}^{4\times4} \Rightarrow 4\times4\times2 = 32$ real parameters
  - unitary $\Rightarrow$ 16 conditions $\Rightarrow$ 16 left
  - re-phasing 4 states $\Rightarrow 16-4 = 12$ left
    - $\Rightarrow 6 = 3+2+1$ mixing angles (4D space!) $\Rightarrow \theta_{12}, \theta_{13}, \theta_{14}, \theta_{23}, \theta_{24}, \theta_{34}$
    - $\Rightarrow$ 6 phases left:
      - × if Dirac, 3 further states can be rephased (look at mass matrix!)
      - × thus: 3 Dirac CP phases $\Rightarrow \delta_1, \delta_2, \delta_3$
        3 Majorana CP phases $\Rightarrow \alpha, \beta, \gamma$
  - in addition: one more mass m_4
  - in principle: extension to even more sterile neutrinos possible
- mass schemes: similar to the case of Δm^2_A, experiments did not deliver high enough statistics to determine the sign of $\Delta m^2_{sterile}$, and also its value is uncertain

$\Rightarrow$ there could be different mass schemes:

see next page



disfavoured by cosmology

+ variants, depending on the scheme of active ν's

- data:
  - appearance experiments (accelerator neutrinos such as ~~e.g.~~ LSND):

$$\boxed{\begin{aligned} &\Delta m^2_{sterile} \sim 0.2 - 0.8\,\mathrm{eV}^2 \\ &\sin^2(2\theta_{\mu e}) \equiv 4|U_{e4}|^2|U_{\mu 4}|^2 \sim 5\cdot 10^{-3} - 3\cdot 10^{-2} \end{aligned}}$$

$\Rightarrow$ data can be fitted well

  - disappearance data (reactor neutrinos, solar neutrinos, accelerator disappearance):

$$\boxed{\begin{aligned} &\Delta m^2_{sterile} \sim 0.1 - 10\,\mathrm{eV}^2 \text{ (hardly constrained)} \\ &\sin^2(2\theta_{\mu e}) \lesssim 4\cdot 10^{-3} \end{aligned}}$$

$\Rightarrow$ apparent ~~dis~~ disagreement between the data sets ↯

$\Rightarrow$ no clear picture for sterile neutrinos

  - 5ν-mixing instead $\Rightarrow$ slight improvement, but tension not resolved

eV-sterile neutrinos in cosmology:

- What would eV-scale sterile neutrinos with active-sterile mixings of $\mathcal{O}(0.1)$ imply?

↳ already seen: active neutrinos contribute to the history of the Universe

$\Rightarrow$ if active-sterile mixings are as large as $\mathcal{O}(0.1)$, then the "sterile" ν's are not really sterile and are in thermal equilibrium in the early Universe

- N_{eff}: measure for the amount of non-photonic radiation in the early Universe (actually not sooo early, e.g., at BBN or CMB time)
- distribution function (see lecture 2):

$$f_\nu(p, T_\nu) = \frac{1}{e^{p/T_\nu}+1} \quad \text{for each species}$$

(6.4)

$\Rightarrow$ energy density: $\rho_{\nu+\bar\nu} = 2 \cdot \int \frac{d^3p}{(2\pi)^3} E\, f(p, T_\nu) \underset{m_\nu \ll T_\nu}{\simeq} \frac{2}{2\pi^2} T_\nu^4 \underbrace{\int_0^\infty dx \frac{x^3}{e^x+1}}_{=\frac{7\pi^4}{120}}$

$\Rightarrow$ energy density of $\frac{7\pi^2}{120} T_\nu^4$ per ν-species

↳ photon temperature: $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$

$\Rightarrow$ with $\rho_\gamma = 2 \cdot \int \frac{d^3p}{(2\pi)^3} \frac{p}{e^{p/T_\gamma}-1} = \frac{\pi^2}{15} T_\gamma^4$:

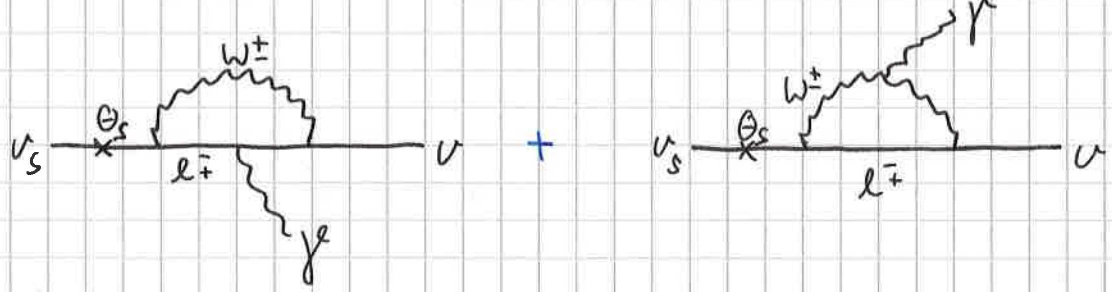
$$\rho_{rad} = \rho_\gamma + N_{eff}\, \rho_{\nu+\bar\nu} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]$$

measures the effective number of neutrino-species

- SM: $N_{eff} = 3$ (actually, due to e^+e^--annihilations: 3.046)
  $\Rightarrow$ with one additional generation of sterile ν's which thermalises:
  $$N_{eff} = 3.046 + 1 \approx 4$$
- BUT: Planck 2015 $\Rightarrow$ $N_{eff} = 3.04 \pm 0.33$
  $\Rightarrow$ cosmology disfavours eV-scale sterile ν's by about 3σ
- HOWEVER: • ν_s may have much smaller mixing $\Rightarrow$ no thermalisation
  • there may be some dilution mechanism at work
  ↳ several examples known

$\boxed{\text{keV-sterile } \nu\text{'s as Dark Matter:}}$ → ask Max Totzauer

- after all, sterile ν's are electrically neutral and massive
  $\Rightarrow$ Could they be the Dark Matter?
- if that was the case, sterile neutrinos would need to fulfill certain requirements:
  • fermionic DM $\Rightarrow$ phase-space density $\gtrsim$ degenerate Fermi-gas
  $\Rightarrow$ this already imposes a bound if sterile ν's make up all the DM: $\boxed{m_s \gtrsim 1\,\text{keV}}$ ("Tremaine-Gunn bound")
  • if active-sterile mixing $\neq 0$, this type of DM may decay:



$\Rightarrow$ sterile neutrinos can decay as:

$\boxed{\nu_s \to \nu\gamma}$ $\Rightarrow$ monoenergetic X-ray photon

↳ decay rate: $\Gamma \sim m_s^5 \theta^2$

$\Rightarrow$ even stronger than the requirement for DM to have a life-time larger than the age of the Universe, there is a strong observational bound from not observing such photons:

$\boxed{(m_s/\mathrm{keV})^5\, \theta_s^2 \lesssim 10^{-6}}$ $\Rightarrow$ θ_s at most $\sim 10^{-3} - 10^{-4}$

- one needs a suitable production mechanism:
  - thermal freeze-out does NOT work (because: θ_s too small)
  - mechanism must produce the right amount of DM
  - DM must be sufficiently slow (i.e., not hot) in order not to spoil cosmological structure formation
    ↳ depending on the details of the production mechanism, keV-sterile neutrino DM can be cold, warm, or hot

- first proposal: Dodelson & Widrow '93 $\Rightarrow$ production through admixtures
  - active-sterile mixing too small for freeze-out
  - BUT: since $\theta_s \neq 0$, ν_s could nevertheless have been produced from the plasma

↳ e.g.:

$\Rightarrow$ rate $|\theta_s|^2$

↳ note: this is often referred to as "non-resonant oscillations", but this is in fact not very precise

(6.6)

- this mechanism can generate the correct abundance:

$$\boxed{\Omega_{DW} h^2 \approx 0.2 \cdot \frac{\sin^2\theta_s}{3\cdot 10^{-9}} \left(\frac{m_s}{3\,\mathrm{keV}}\right)^{1.8}}$$

- HOWEVER: DM produced by this mechanism is either too hot or in conflict with the X-ray bound

- further production mechanisms:
  - Shi-Fuller mechanism: resonant enhancement of active-sterile transitions due to ~~[illegible]~~ background lepton asymmetry (BUT: theoretically unnatural)
  - thermal overproduction ("far" beyond the SM) + subsequent entropy dilution
    ↳ close to being in trouble with BBN
  - production by (scalar) decays: e.g. $S \to \nu_s \nu_s$, where S is produced e.g. by freeze-out or freeze-in ⇒ quite versatile, strong relations to BSM-physics
    ↳ ask Max Totzauer

- additional constraints:
  - BBN should not be disturbed
  - 3.5 keV-line signal (if real) ⇒ SF-mechanism tends to be too warm
  - structure formation: DM should be "cold" or "warm"
    ↳ details are complicated, but in general all production mechanisms are constrained by this

- if WIMPs continue to be more and more strongly constrained, ~~[illegible]~~ keV-sterile neutrinos may become a very attractive alternative