Neutrino masses and leptogenesis

from small lepton number violation

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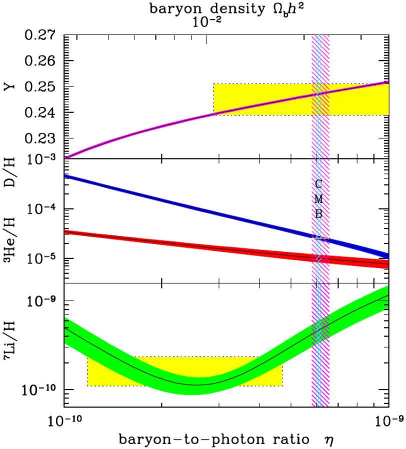
Moriond 2018
based on
1507.06215, 1709.00414
in collaboration with
A. Abada, G. Arcadi,
and M. Lucente

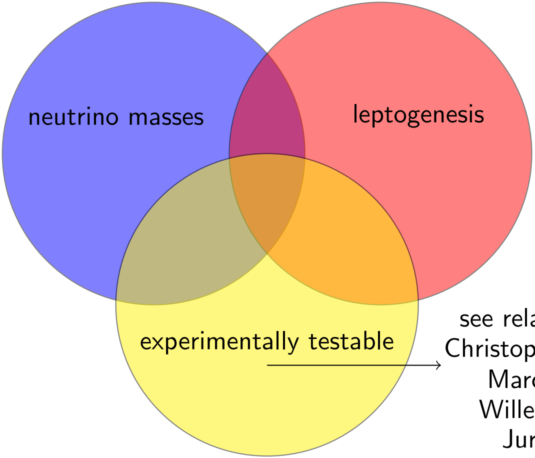
The observed baryon asymmetry of the Universe



[Particle Data Group]

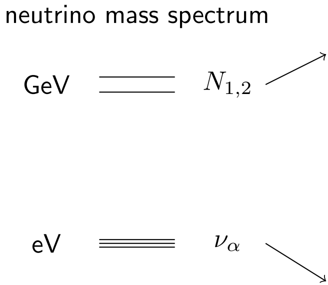
- tiny matter-antimatter asymmetry in the early universe
- as particles and anti-particles annihilate, tiny asymmetry results in matter dominated Universe
- Sakharov conditions for dynamical generation [Sakharov '67]
  - violation of B (or L)
  - violation of C and CP
  - departure from thermal equilibrium

Motivation & Outline



see related talks by:
Christopher Parkinson,
Marco Drewes,
Willem Verbeke,
Juraj Klaric,
Xabier Marcano,
Giulia Negro,
Jacobo Lopez Pavon

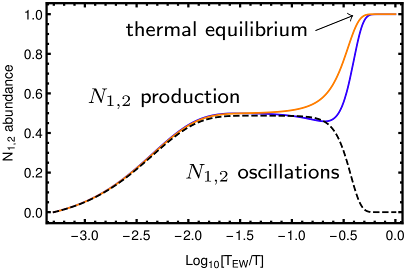
Leptogensis through neutrino oscillations

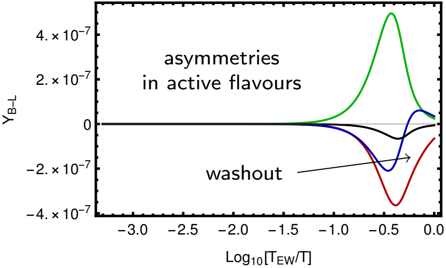


neutrino mass spectrum

GeV $N_{1,2}$

eV ν_α





Leptogenesis through neutrino oscillations

[Akhmedov, Rubakov, Smirnov '98]

- nearly degenerate right-handed Majorana neutrinos N with $M_N \sim$ MeV - GeV and weak coupling to SM, $h_\nu \sim 10^{-7\pm 2}$
- starting from a vanishing initial abundance, Ns are thermally produced but do not reach full thermal equilibrium before the EW phase transition ($=$ sphaleron freeze-out)
- N_R oscillations create a CP violating background for the active neutrinos

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- N_R oscillations create a CP violating background for the active neutrinos
- defining a generalized lepton number $\mathcal{L}$ under which also the Ns are charged, both the active and sterile sector develop a $\Delta\mathcal{L}$ of equal magnitude but opposite sign (for $M_N \gg T$)
- Sphaleron processes only pick up the $\Delta\mathcal{L} = \Delta L$ of the active sector, leading to a net baryon asymmetry

low-scale leptogenesis mechanism → experimentally accessible !

Boltzmann equations

Kinetic equations for neutrino density matrix $\rho_{AB}, \quad A, B \in \{N, \bar{N}, \nu, \bar{\nu}\}$

$$i\frac{d\rho}{dt} = [H, \rho] - \frac{i}{2}\{\Gamma, \rho\} + \frac{i}{2}\{\Gamma^p, I - \rho\}$$

[Sigl, Raffelt '93]

Assuming $M_N \gg m_\nu$: active-sterile oscillations suppressed,
kinetic equilibrium: $\rho_{NN}(T,k) = R_N(T)\rho^{\text{eq}}_{NN}(T,k)$,
thermal equilibrium for active ν: $\rho_{\nu,\bar{\nu}} \sim \rho_{\text{eq}}(T,k)\exp\left[\pm\text{diag}(\mu_{L_\alpha})\right]$:

$$\begin{aligned}\frac{dR_N}{dt} =& -i\left[\langle H\rangle, R_N\right] - \frac{1}{2}\langle\gamma^{(0)}\rangle\left\{F^\dagger F, R_N - I\right\} - \frac{1}{2}\langle\gamma^{(1b)}\rangle\left\{F^\dagger \mu_L F, R_N\right\}\\ &+ \langle\gamma^{(1a)}\rangle F^\dagger \mu_L F\,,\\ \frac{d\mu_{\Delta\alpha}}{dt} =& -\frac{9\,\zeta(3)}{2N_D\,\pi^2}\Big\{\langle\gamma^{(0)}\rangle\left(FR_NF^\dagger - F^*R_{\bar{N}}F^T\right) - 2\langle\gamma^{(1a)}\rangle\mu_L FF^\dagger +\\ &+ \langle\gamma^{(1b)}\rangle\mu_L\left(FR_NF^\dagger + F^*R_{\bar{N}}F^T\right)\Big\}_{\alpha\alpha}\,,\end{aligned}$$

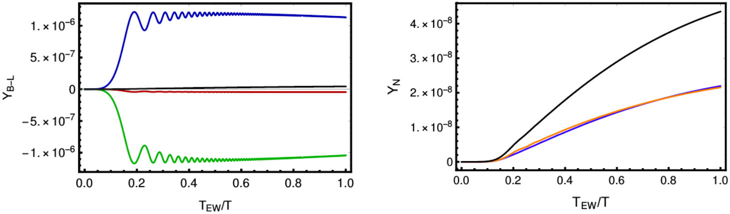
[Asaka, Shaposhnikov '05]

w. F = Yukawa coupling in mass basis, H = eff. Hamiltonian, $\langle\cdot\rangle$ = thermal average

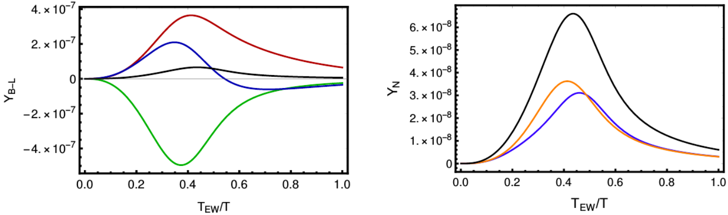
Benchmark solutions

[Abada, Arcadi, VD, Lucente '15, '17]

weak washout regime, $|F| \lesssim 10^{-7}$ (analytical solutions available)



intermediate/strong washout regime, $|F| \sim 10^{-6}$ (perturbative expansion)



Neutrino mass models for ARS leptogenesis

Inverse Seesaw [Wyler, Wolfenstein '83; Mohapatra, Valle '86]

(schematically for 'active', 'RH', 'sterile')

$$M_\nu = \underbrace{\begin{pmatrix} 0 & \frac{1}{\sqrt{2}} h_\nu v & 0 \\ \frac{1}{\sqrt{2}} h_\nu v & 0 & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}}_{\text{L conserving}} + \xi \underbrace{\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \Lambda \end{pmatrix}}_{\Delta L = 2}$$

$$\Rightarrow \quad m_\nu \simeq \frac{\xi (h_\nu v)^2}{2\Lambda}\,, \qquad \Delta m^2 = M_{N_2}^2 - M_{N_1}^2 \simeq 2\xi\Lambda^2$$

Small neutrino masses and small mass splitting generated by the same small lepton number violation (LNV) parameter

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Linear Seesaw [Barr '04; Malinsky, Romao, Valle '05]

$$M_\nu = \underbrace{\begin{pmatrix} 0 & \frac{1}{\sqrt{2}} h_\nu v & 0 \\ \frac{1}{\sqrt{2}} h_\nu v & 0 & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}}_{\text{L conserving}} + \epsilon \underbrace{\begin{pmatrix} 0 & 0 & \frac{1}{\sqrt{2}} h'_\nu v \\ 0 & 0 & 0 \\ \frac{1}{\sqrt{2}} h'_\nu v & 0 & 0 \end{pmatrix}}_{\Delta L = 2}$$

$$\Rightarrow \quad m_\nu \simeq \frac{\epsilon (h_\nu v)^2}{\Lambda}\,, \qquad \Delta m^2 = M_{N_2}^2 - M_{N_1}^2 \simeq 2\epsilon (h_\nu v)^2$$

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Linear Seesaw [Barr '04; Malinsky, Romao, Valle '05] plus Inverse Seesaw

$$M_\nu = \underbrace{\begin{pmatrix} 0 & \frac{1}{\sqrt{2}} h_\nu v & 0 \\ \frac{1}{\sqrt{2}} h_\nu v & 0 & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix}}_{\text{L conserving}} + \epsilon \underbrace{\begin{pmatrix} 0 & 0 & \frac{1}{\sqrt{2}} h'_\nu v \\ 0 & 0 & 0 \\ \frac{1}{\sqrt{2}} h'_\nu v & 0 & \frac{\xi}{\epsilon}\Lambda \end{pmatrix}}_{\Delta L = 2}$$

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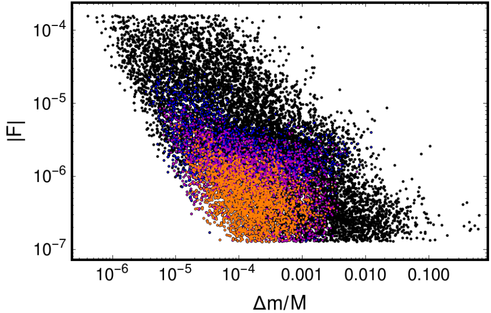
Strategy

[Abada, Arcadi, VD, Lucente '15,'17]

- Generate data points which respect all constraints on active neutrino masses/mixings as well as laboratory constraints on sterile neutrinos
$\Rightarrow$ minimial models: LISS(1,1), ISS(2,2), ISS(2,3) [Abada, Lucente '14]
- Calculate baryon asymmetry by solving Boltzmann equations
  - analytically in the weak washout regime
  - perturbative numerical procedure otherwise
- $\Rightarrow$ requirements for successful leptogenesis:
constraints on masses, Yukawa couplings, mixing angles...
- $\Rightarrow$ motivates parameter regions to focus experimental searches

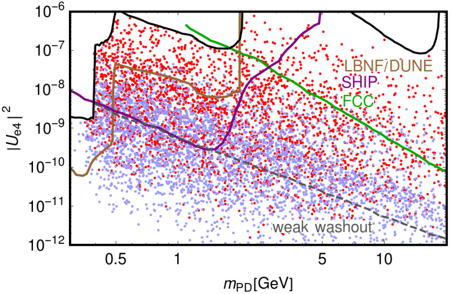
Neutrino mass models for ARS leptogenesis



here: LISS + strong washout

Yukawa coupling
and mass splitting.
coloured: $\eta_b \geq \eta_b^{\text{obs}}$

mixing and mass scale
for NH and IH



An example: dark matter in the ISS(2,3)

$M_{\text{PD}} \longrightarrow$ decouple

GeV m_{PD} $\Delta m \sim$ keV $\longrightarrow$ leptogenesis

keV $m_{\text{DM}} \longrightarrow$ dark matter
(Dodelson-Widrow)

eV $m_\nu \longrightarrow$ ν oscillations

with

$$\frac{m_{\text{DM}}}{m_{\text{PD}}} \simeq \frac{\Delta m}{m_{\text{PD}}} \simeq 10^{-3} \left(\frac{10^{-5}}{|F|}\right) \left(\frac{m_{\text{PD}}}{\text{GeV}}\right)^{1/2} \left(\frac{m_\nu}{0.05\ \text{eV}}\right)^{1/2}$$

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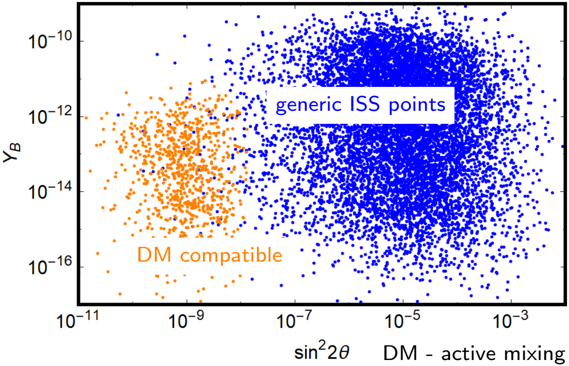

ISS + ARS leptogenesis too constraining on mixing angles

Conclusion

- observed matter-antimatter asymmetry requires BSM physics
- leptogenesis through neutrino oscillations provides a testable mechanism
  - oscillations of GeV right-handed neutrinos before EW phase transition
  - nonzero lepton number in the active sector
  - transmitted to baryons through sphaleron processes
- Generic predictions (mass range, sizeable active sterile mixing) but also sensitivity to underlying neutrino mass model
  - symmetry inspired vs minimal tuning
  - strong washout vs weak washout
  - minimal particle content vs minimal parameters
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Thank you!