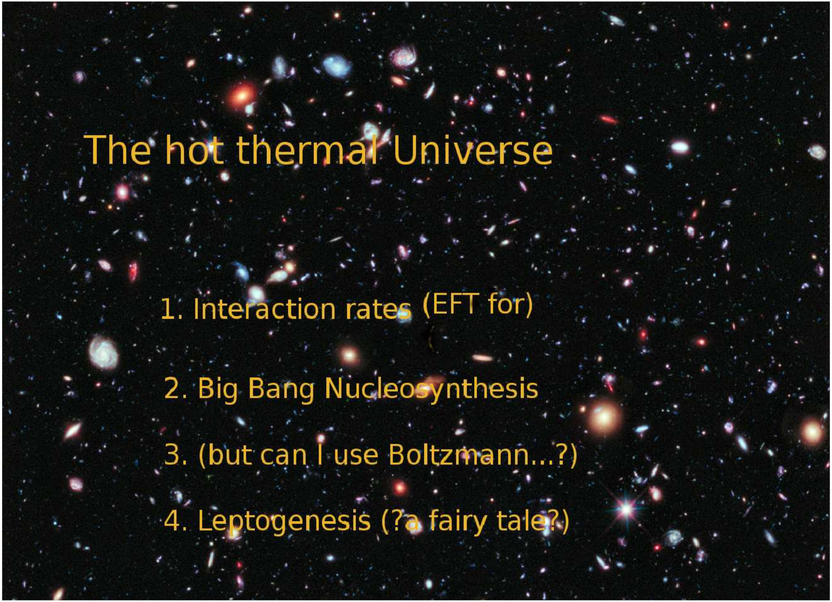
The hot thermal Universe
1. Interaction rates (EFT for)
2. Big Bang Nucleosynthesis
3. (but can I use Boltzmann...?)
4. Leptogenesis (?a fairy tale?)

Neutrinos in cosmology

- leptogenesis : $T : 10^{12} \to 100$ GeV, generate a lepton asym in CPV dynamics, use SM B+L Violation to transform to baryons
- Big Bang Nucleosynthesis ($H, D,^3 He,^4 He,^7 Li$ at $T \sim$MeV)
  how many species of relativistic ν in the thermal soup ?
- decoupling of photons —$e+p \to H$ (CMB spectrum today)
  cares about radiation density $\leftrightarrow N_\nu, m_\nu$

...all about interaction rates of particles in the U...

- EFT = recipe to study observables at scale ℓ
  1. choose *appropriate* variables to describe *relevant* dynamics
  2. 0th order interactions, by sending all parameters $\begin{cases} L \gg \ell & \to \infty \\ \delta \ll \ell & \to 0 \end{cases}$
  3. then perturb in ℓ/L and δ/ℓ

an "EFT" for particle interactions in the early U ?

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Example : interactions in the early Universe of age τ_U ($\tau_U \sim 10^{-24}$ sec)

⋆ processes with $\tau_{int} \gg \tau_U$ ...neglect !

⋆ processes with $\tau_{int} \ll \tau_U$ ...assume in thermal equilibrium !

⋆ processes with $\tau_{int} \sim \tau_U$ ...calculate this dynamics

⋆ can then do pert. theory in slow interactions and departures from thermal equil.

Suppose the density of the U is dominated by relativistic particles in equilibrium ($\rho \propto T^4$)

$$H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G}{3}\frac{g_{eff}\pi^2 T^4}{30}} \simeq \frac{1.7\sqrt{g_{eff}}}{m_{pl}}T^2 \quad , \quad g_{eff} \equiv \sum_{\bar{b},b} g_b + \frac{7}{8}\sum_{\bar{f},f} g_f$$

and $T(t) \sim 1/a(t) \Rightarrow a(t) = \sqrt{t/t_0}$, so

$$\tau_U(T) = \frac{1}{2H} \qquad \Rightarrow \qquad \tau_U(sec) \simeq 0.7\frac{MeV^2}{T^2}$$

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Can estimate interaction rate of a particle in the plasma as

$$\Gamma_{int} \sim \frac{1}{\tau_{int}} \sim \beta \times n_{target} \times \sigma \sim \frac{gT^3}{\pi^2} \sigma$$

(lets forget IR divergences) For a e^- interacting with a bath of γs :

$$\beta\sigma(e\gamma \to e\gamma) = \frac{2\pi\alpha^2}{s} \ln \frac{s}{m_e^2}$$

For $s = (3T)^2$ (?or $s = T^2$) and $\sqrt{g_{eff}} \sim 10$:

$$\frac{\Gamma}{H} \sim \frac{g_\gamma T^3}{\pi^2} \frac{2\pi\alpha^2}{9T^2} \frac{1}{H} \sim \frac{m_{pl}}{3 \times 10^6 T}$$

$\Rightarrow e^-, \gamma$ in thermal equil for $T \lesssim 10^{13}$ GeV. Ditto e^+...
unbroken SU(N) : same scaling of $\Gamma/H(T)$, rate a bit bigger.

Another example : $(\nu e \to \nu e)$ at $T \ll m_W$

Interaction rate of a $\nu_{\mu,\tau}$ with $e^{\pm}$ (neglect rare n,p) :

$$\frac{\Gamma}{H} \sim \frac{g_{e^\pm} T^3}{\pi^2} \sigma \frac{1}{H} \quad \text{with} \quad \sigma \simeq \frac{G_F^2 s}{16\pi}$$

So $\Gamma \sim H$ when

$$\Gamma \sim \frac{G_F^2 T^5}{4\pi} \sim \frac{1.66\sqrt{g_{eff}}\, T^2}{m_{pl}}$$

$\Rightarrow$ neutrinos acquire equilibrium densities before $T \sim$ MeV.
$\nu_{\mu,\tau}, \overline{\nu}_{\mu,\tau}$ decouple from $e^{\pm}$ around $T \simeq 3.5$ MeV,
ν_e has also W exchange diagram = remain in equilibrium til $T \sim 2$ MeV.

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Decouple at $T \gg m_\nu$, so *retain* relativistic number distribution 'til today
$\Rightarrow$ there is a Cosmic Neutrino BackGround.
(But $T_\nu = (4/11)^{1/3} T_\gamma$, because $e^\pm$ annihilation heats γ wrt ν)

(Exercise : *how to detect CNB ?*)

In the room, are $\sim 10^6$ WIMPS, $\sim 10^5$ Be ν, and $\sim 10^{10}$ Cosmic Background Neutrinos(CNB).

How to detect CNB ?

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What about ν capture βdecay : $n + \nu_{CNB} \to p + e$?

Weinberg
Cocco Mangano
Messina

To compare rates for ${}^3H \to {}^3He + e + \bar{\nu}_e$ to $\nu_e + {}^3H \to {}^3He + e$:

$$\frac{n_{\nu CNB}}{\nu \text{ phase space}} \simeq \frac{T^3_{CNB}}{\pi^2}\frac{1}{Q^3} \sim \left(\frac{10^{-4}\text{eV}}{20\text{keV}}\right)^3 \sim 10^{-24}$$

But...$E_e = Q + m_\nu$
(recall for ${}^3H \to {}^3He + e + \bar{\nu}_e$, $E_e \leq Q - m_\nu$)

So...if ever resolution better than m_ν...PTOLEMY !

What rate associated to neutrino masses $m_D \bar{\nu}_L \nu_R$?

1. below m_W/after EWPT(Elec.Weak PhaseTransition) : m^2-correction to gauge scattering

$$\frac{m_\nu^2 G_F^2}{4\pi} T^3 > \frac{1.7 g_{eff} T^2}{m_{pl}} \Leftrightarrow m_\nu \gtrsim 100 \text{ keV}$$

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2. above m_t/before EWPT :
scattering via neutrino Yukawa : $\lambda\bar{\ell}H\nu_R$ (attach other end of Higgs to $t\bar{t}$)

$$\frac{\lambda^2}{4\pi} T > \frac{1.7 g_{eff} T^2}{m_{pl}} \Leftrightarrow \lambda \gtrsim 10^{-8}$$

($m_D\overline{\nu_L}\nu_R \sim$ few $\times$ keV $\overline{\nu_L}\nu_R$)

Despite that there are six light chiral fermions in the model with Dirac ν-masses, only three are "in equilibrium" in the early U $\Leftrightarrow$ contribute to the radiation energy density.

BBN bounds on N_ν

Weinberg, "The First Three Minutes"
IoccoEtal, P Rep 472(2009)1

code PArthENoPE 0705.0290

$N_\nu \equiv$ number of 2-comp. relativistic νs with equilibrium energy density

Big Bang Nucleosynthesis makes D,^{3}He,^{4}He,Li at $T \lesssim$ MeV, $\tau_U \sim$ few minutes) :

- neutrons crucial to form $D,^{3,4} He, Li$
- $n_n/n_p \propto exp\{-(m_n - m_p)/T\}$ in thermal equil at $T \gtrsim$ MeV
- "freezes" when $\Gamma(n + \nu \to p + e) \lesssim H \simeq \sqrt{3\rho_{rad}/m_{pl}^2}$; $\rho_{rad} \supset \{\gamma, N_\nu \nu\}$

$\Rightarrow$ "primordial" abundances of $D,^{3,4} He, Li$ constrain

$$N_\nu \lesssim 4.08$$

Mangano, Serpico

NB : this is a dynamical process : reliable predictions from complex codes accounting for multiple nuclear processes.

1. consider U at $T \sim$ MeV, (nuclear binding $\sim$ MeV)
$T \ll \Lambda_{QCD} \Rightarrow$ all baryons are n or p, and rare : $n_{B-\bar{B}}/n_\gamma \sim \eta \sim 10^{-9}$.
$\Rightarrow$ bind into light nuclei via 2-body processes :

$$\begin{aligned} n + p &\leftrightarrow D + \gamma \\ D + D &\leftrightarrow {}^3He + n \\ D + D &\leftrightarrow T + p \\ D + D &\leftrightarrow {}^4He + \gamma \\ D + T &\leftrightarrow {}^4He + n \\ D + {}^3He &\leftrightarrow {}^4He + p \\ {}^3He + {}^3He &\leftrightarrow {}^4He + 2p \\ &\ldots \end{aligned}$$

$\Rightarrow$ need first to make D. $E_{bind} = 2.2$ MeV.
Rates are fast, but baryons are rare : newly born D needs to meet another baryon before a $E > 2.2$ MeV photon :

$$n_\gamma(E > 2.2MeV) \sim e^{-2.2\mathrm{MeV}/T} n_\gamma \lesssim 10^{-9} n_\gamma \Rightarrow T \lesssim .1 \ \mathrm{MeV}$$

2. How many n and p when can make D? If $\Gamma(n \leftrightarrow p) \sim T^5/m_W^4 > H$, obtain equilibrium ratio $n_n/n_p = e^{-\Delta m/T}$, ($\Delta m = 1.293$ MeV).

$n \leftrightarrow p$ interactions are $p + e \leftrightarrow n + \nu$, $n + e^+ \leftrightarrow p + \bar{\nu}$, $n \leftrightarrow p + e^- + \bar{\nu}$ and

$$H = \frac{1}{m_{pl}} \sqrt{\frac{8\pi\rho}{3}} = \frac{1.77\sqrt{g_{eff}}}{m_{pl}} T^2 \quad , \quad g_{eff} = 2 + \frac{7}{8}(4 + 2N_\nu)$$

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"Freezeout" of $\Gamma(n \leftrightarrow p)$ at $T_f \sim 0.7$ MeV, for $N_\nu = 3$.
(After freezeout, n_n/n_p decreases due to n decay :
$n_n/n_p = \exp\{-\Delta m/T_f\} e^{-t/\tau_n}$, where $\tau(n \to pe\bar{\nu}) \sim 881$ sec.)

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3 When $n_\gamma(E > 2.2 \text{ MeV}) \lesssim n_B$, available ns to ^4He! Upper bound on ^4He abundance today (stars add ^4He) $\Rightarrow$ upper bound on N_ν.
For larger N_ν, freezeout *earlier*, so $T_f \nearrow$ and n_n/n_p larger.

3. Cosmic Microwave Background :(=fit to a multi-param. model...).
Roller coaster at $\ell > 150$ is a snapshot of sound waves in the plasma at recomb ; amplitude cares about ρ_b/ρ_γ. Is sensitive to time since mat-rad equality, which is sensitive to N_ν...but can compensate by changing other parameters !
PDB discussion of Verde-Lesgourges :
suppose other inputs cancel LO effect no N_ν ... what remains ?
Argue that remaining effects cannot be cancelled by ajusting parmeters, so obtain :

$$N_\nu \lesssim 3.3 \pm 0.5$$

PLANCK 13
more restrictive with
other cosmo input

So far, compute on "back of envelope". Recall recipe :

To identify relevant interactions in the early Universe of age τ_U
($\tau_U \sim 10^{-24}$ sec)

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...sloppy is fine for 1,2 ; but if really want to calculate dynamics, need eqns for 3. ?

Dynamical Eqns : can one use Boltzmann Eqns ? ? ?

Ludwig Boltzmann : 1844-1906 / Max Planck : 1858-1947 ($\hbar \sim 1900$)

early U : $\rho \propto T^4 >$ nucleus for $T > 100$ MeV
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Why is that? Ask the closed-time-path, finite-density Path Integral for Eqns of motion for the number operator...Density Matrix Eqns, Real-Time Finite-Temp Field Theory/ 2Particle- Irreducible Eqns/ Kadanov-Baym/Schwinger-Dyson Eqns)

$$\frac{d}{dt}\hat{n} = +i[\hat{H}_0, \hat{n}] - [\hat{H}_I, [\hat{H}_I, \hat{n}]] + ...$$

(2nd Quant.,Heisenberg rep, t-dep ops)
$\hat{H}_0$ = free Hamiltonian Interaction rates from second +... terms.
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...lets suppose we can (usually) use Boltzmann...

Can neutrinos make the Universe we see ?

Leptogenesis

Leptogenesis is a class of recipes, that use majorana neutrino mass models to generate the matter excess. The model generates a lepton asymmetry (before the Electroweak Phase Transition), and the non-perturbative SM B+L violn reprocesses it to a baryon excess.

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PLANCK

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$\Rightarrow$ Question : where did that excess come from ?

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   X no ! After birth of U, there was "inflation"
   - (only theory explaining coherent temperature fluctuations in microwave background that arrive from causally disconnected regions today...)
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3. created/generated/cooked after inflation...

Three ingredients to prepare in the early U (old russian recipe)

Sakharov

1. B violation : if U_{niverse} starts in state of $n_B - n_{\bar{B}} = 0$, need $\not{B}$ to evolve to $n_B - n_{\bar{B}} \neq 0$

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3. out-of-thermal-equilibrium ...equilibrium = static. "generation" = dynamical process
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   From end inflation → BBN, Universe is an expanding, cooling thermal bath, so non-equilibrium from :
   - slow interactions : $\tau_{int} \gg \tau_U$ = age of Universe ($\Gamma_{int} \ll H$)
   - phase transitions :

ingredient 1 : Does the SM conserve B ?

B, L are global symmetries of the SM Lagrangian (q, ℓ doublets, e, u, d singlets)

$$\mathcal{L}_{SM} \supset \overline{q} \not{D} q \ , \ \overline{\ell} \not{D} \ell \ \ , \ \ \overline{\ell} H e \ \ , \ \ \overline{q} \widetilde{H} u \ \ , \ \ \overline{q} H d$$

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But the SM *does not* conserve $B + L$...
In QFT, there is the axial anomaly...
...anomalously, the fermion current associated to a classical symmetry is not conserved.

see Polyakov,
"Gauge Fields + Strings,"
6.3=qualitative effects of instantons

$B + L$ is anomalous. Formally, for one generation(α colour) :

$$\sum_{\substack{SU(\mathbf{2}) \\ \overline{singlets}}} \partial^\mu(\overline{\psi}\gamma_\mu\psi) + \partial^\mu(\overline{\ell}\gamma_\mu\ell) + \partial^\mu(\overline{q}^\alpha\gamma_\mu q_\alpha) \propto \frac{1}{64\pi^2} W^A_{\mu\nu}\widetilde{W}^{\mu\nu A}.$$

where integrating the RHS over space-time counts "winding number" of the SU(2) gauge field configuration.
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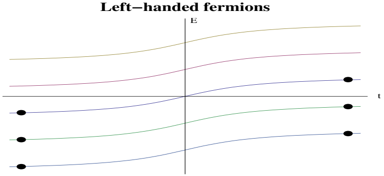

thanks to V Rubakov

't Hooft
Kuzmin Rubakov+
Shaposhnikov

At $T = 0$ is tunneling process (from winding # to next, "instanton") :
$\Gamma \propto e^{-8\pi/g^2}$

At $0 < T < m_W$, can climb over the barrier :

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SM B+L violation : rates

't Hooft
Kuzmin Rubakov+
Shaposhnikov

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$\star\star\star$ SM $\not{B}+\not{L}$ is $\Delta B = \Delta L = 3$ $(= N_f)$. No proton decay ! $\star\star\star$

• Want to make a baryon excess $\equiv Y_B$ after inflation, that corresponds today to ~ 1 baryon per 10^{10} γs.

• Three required ingredients : $\not{B}$, $\not{CP}$, $\not{TE}$.
Present in SM, but hard to combine to give big enough asym Y_B

Cold EW baryogen ? ? Tranberg et al
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⇒ *evidence for physics Beyond the Standard Model (BSM)*

One observation to fit, many new parameters...

⇒ *prefer BSM motivated by other data ⇔ m_ν ⇔ seesaw !* (uses non-pert. SM $\not{B+L}$)

- add 3 singlet N to the SM in charged lepton and N mass bases, at scale $> M_i$:
  $\mathcal{L} = \mathcal{L}_{SM} + (\boldsymbol{\lambda}_{\alpha J}\overline{N}_J \ell_\alpha \cdot H + h.c.) - \frac{1}{2}\overline{N_J} M_J N_J^c$

M_I few GeV $\rightarrow 10^{15}$GeV, $\not{L}$. $\not{CP}$ in $\boldsymbol{\lambda}_{\alpha J} \in \boldsymbol{C}$.

Leptogenesis in the type 1 seesaw : usually a Fairy Tale

Fukugita Yanagida
Buchmuller et al
Covi et al
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If this asymmetry can escape the big bad wolf of thermal equilibrium...

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4 If asymmetry escapes the wolf of thermal equilibrium...

5 the lepton asym gets partially reprocessed to a baryon asym by non-perturbative $B + L$ -violating SM processes ("sphalerons")

And the Universe lived happily ever after, containing many photons. And for every 10^{10} photons, there were 6 extra baryons (wrt anti-baryons).

Does it work ? Calculate something ?

Recipe : calculate suppression factor for each Sakharov condition, multiply together to get Y_B :

$$\frac{n_B - n_{\bar{B}}}{s} \sim \frac{1}{3g_*}\epsilon_{L,CP}\eta_{TE} \sim 10^{-3}\epsilon\eta \qquad (\text{want } 10^{-10})$$

$s \sim g_* n_\gamma$, ϵ = lepton asym in decay, η = $\not{T}\not{E}$ process/γ

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Suppose at $T \gtrsim M_1$, a density $\sim T^3$ is produced.

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Fraction N remaining at T_{ID} when ID turn off :

$$\frac{n_N}{n_\gamma}(T_{ID}) \simeq e^{-M_1/T_{ID}} \simeq \frac{H(T = M_1)}{\Gamma(N \to \ell_\alpha \phi)} \equiv \eta$$

Estimate ϵ, the CP asymmetry in decays

Kolb+Wolfram, NPB '80, Appendix

In leptogenesis, need $\not{CP}$, $\not{L}$ interactions of N_I...for instance :

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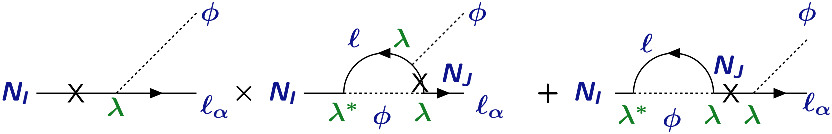

Just try to calculate ϵ_1 ?

• asym at tree × loop, *if* $\not{CP}$ from complex cpling *and* on-shell particles in the loop (divergences cancel in diff, need Im part of Feynman param integrtn)

$\not{C}\not{P}$, complex couplings, loops unitarity and all that...

Kolb+Wolfram, NPB '80, Appendix

1 the S-matrix $\boldsymbol{S} \equiv \mathbf{1} + i\boldsymbol{T}$ is CPT invariant

$$\langle\overline{\phi\ell}|\boldsymbol{S}|N\rangle = \langle N|\boldsymbol{S}|\phi\ell\rangle \quad (= \langle\phi\ell|\boldsymbol{S}^\dagger|N\rangle^*)$$

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2 We are interested in a $\not{CP}$ asymmetry :

$$\epsilon \propto \int d\Pi\Big(|\langle\phi\ell|\boldsymbol{T}|N\rangle|^2 - \langle\overline{\phi\ell}|\boldsymbol{T}|N\rangle|^2\Big)$$

SO (this formula exact, if I kept 2s and sums)

$$\epsilon \propto \boldsymbol{Im}\Big\{\langle\phi\ell|\boldsymbol{T}^\dagger|N\rangle\langle N|\boldsymbol{T}\boldsymbol{T}^\dagger|\phi\ell\rangle\Big\}$$

$\Rightarrow$ need complex cplings, and on-shell particles in a loop

Can use unitarity and CPT invariance of S-matrix to estimate ϵ from tree amplitudes.
Consider $M_1 \ll M_{2,3}$, asym from $\not{CP}$, $\not{L}$ decays of N_1 :

$$\epsilon_1^\alpha = \frac{\Gamma(N_1 \to \phi \ell_\alpha) - \Gamma(\bar{N}_1 \to \bar{\phi}\bar{\ell}_\alpha)}{\Gamma(N_1 \to \phi \ell) + \Gamma(\bar{N}_I \to \bar{\phi}\bar{\ell})} \qquad (\text{recall } N_1 = \bar{N}_1)$$

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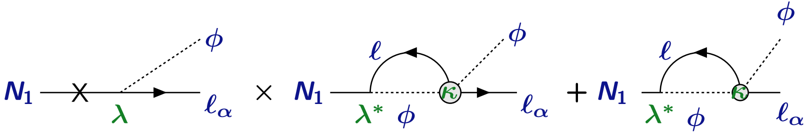

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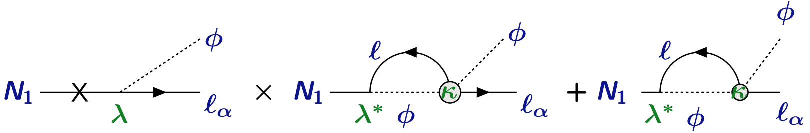

$$\epsilon_1 \sim \frac{1}{8\pi} \frac{\lambda^2 \kappa}{\lambda^2} M \quad < \quad \frac{3}{8\pi} \frac{m_\nu^{max} M_1}{v^2} \quad \sim 10^{-6} \frac{M_1}{10^9 \text{GeV}}$$

Estimate Y_B

Recall($s \sim g_* n_\gamma$, ϵ = lepton asym in decay $\eta = \not{TE}$ process/γ) :

$$\frac{n_B - n_{\bar{B}}}{s} \sim \frac{1}{3g_*}\epsilon_{L,CP}\eta_{TE} \sim 10^{-3}\epsilon\eta \qquad (\text{want } 10^{-10})$$

$$\sim 10^{-3}\frac{H}{\Gamma}10^{-6}\frac{M_1}{10^9\text{GeV}}$$

for $M_1 \ll M_{2,3}$, need $M_1 \gtrsim 10^9$ GeV to obtain sufficient ϵ

?but give $\delta m_H^2 \gg m_H^2$?

For $M_I \sim M_J \Leftrightarrow$ resonantly enhance ϵ ... up to $\epsilon \lesssim 1/8\pi$!
but need decays before Electroweak PT (to profit from sphalerons)... and ID out-of-equil :

$$\Gamma_{ID} \sim e^{-M/T}\Gamma(N \to \phi\ell) < H \quad \Rightarrow \quad M \gtrsim 10\,T_c$$

Fairy tale works for degen N_I for $M_I \gtrsim$ TeV

do leptogenesis with $M_K < 10^7$ GeV ?

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But unverifiable ?
+ credibility enhanced if measure Majorana m_ν ($0\nu 2\beta$)
+ and if measure $\not{CP}$ in the lepton sector
(but no dependence of $\not{CP}$ for leptogen on low energy $\not{CP}$ = other phases also contribute, so leptogen can work with vanishing low-E CPV, and fail with non-zero CPV at low-E)
− scenario ruled out if measure Dirac m_ν

νMSM : type 1 seesaw below 100 GeV gives BAU and DM

AkhmedovRubakovSmirnov
Asaka + Shaposhnikov
thesis Canetti
...

ingredients : SM +

$N_{2,3}$: 100 MeV $\lesssim M_{2,3} \lesssim$ 10 GeV, $\Delta M \lesssim \begin{cases} 10^{-6}\ \mathrm{eV} & Y_B, \Omega_{DM} \\ \mathrm{keV} & Y_B, NOT\ \Omega_{DM} \end{cases}$

Yukawas $\ni$ give 2 light SM neutrinos via seesaw

N_1 : $M_1 \sim$ keV. WDM candidate.

feebly coupled (negligeable contribution $m_{\nu,SM}$)

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scenario :

Population of $N_{2,3}$ produced via Yukawas before EPT

Produce $\Delta L \to Y_B$ via oscillations of $N_{2,3}, \nu_{SM}$ before EPT

Produce $\Delta L \gtrsim 10^{-5}$ via osc. and decay of $N_{2,3}$ after EPT

Can produce sufficient distribution of N_1 via osc.

tests :

$N_{2,3}$: beam dump, SHIP

N_1 as DM : X-rays from DM decay, WDM bounds (depend on momentum distribution)

How does asym generation work ? (very simplified !)

1 at $T \lesssim TeV$ (recall $\lambda \lesssim 10^{-7}$) , produce N_2, N_3 via Yukawa interaction $\lambda \overline{N} \ell \cdot \phi$

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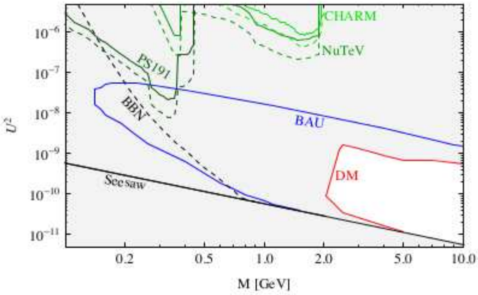
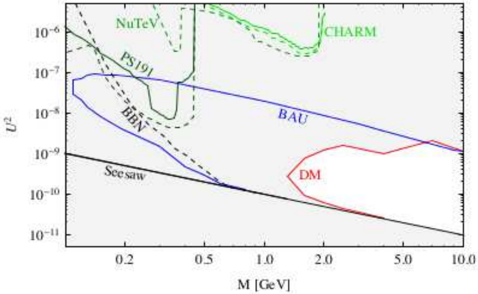
3 back to ν_L via λ
at $\tau_U \sim \tau_{osc}$, 1,2,3 are *coherent*, so CPV from λ-ΔM^2-λ gives flavour asyms in $\nu_{L\alpha}$ (to small)
lepton number in $\ell_L + N_R$ is conserved (actually, L_{SM}+ helicity of N_I)
from $\tau_{osc} \to \tau_{EWPT}$, asyms in $\nu_{L\alpha}$ seed asyms in $N \longrightarrow$ asyms in $\nu_{L\alpha}$ (enough asym)
...works also in detailed calculations with all available technology...
(eg also include lepton number violating interactions)

Teresi Hambye
Eijima + Shaposhnikov
Ghiglieri+ Laine





$$U^2 = \mathrm{Tr}[\lambda M^{-2} \lambda^\dagger]$$

Summary

Leptogenesis is a class of recipes, that use majorana neutrino mass models to generate the matter excess. The model generates a lepton asymmetry (before the Electroweak Phase Transition), and the non-perturbative SM B+L violn reprocesses it to a baryon excess.

⋆ efficient, to use the BSM for m_ν to generate the Baryon Asym.

⋆ using SM B+L violn ($\Delta B = \Delta L = 3$) avoids proton lifetime bound

⋆ *it works* ...rather well, for a wide range of parameters