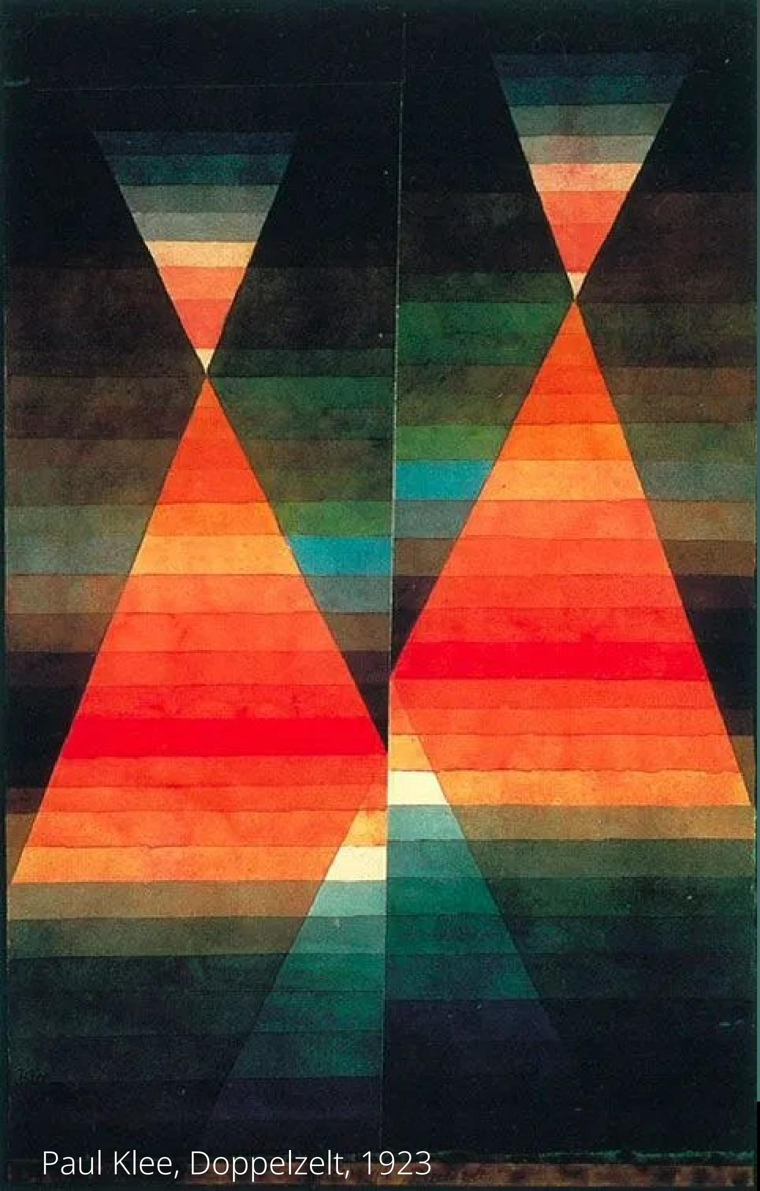


Paul Klee, Doppelzelt, 1923

EuCAPT

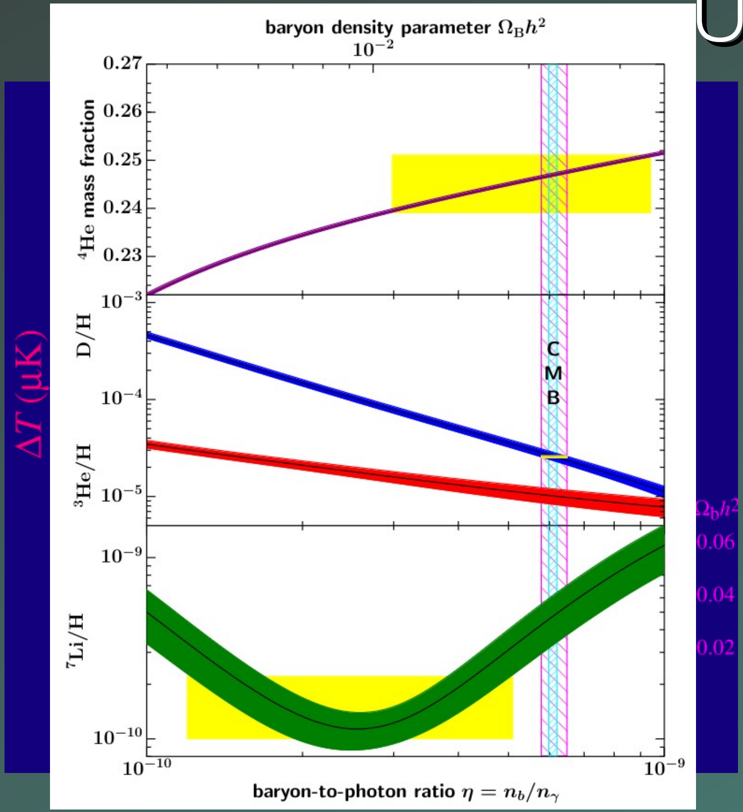
Bayrogenesis and Leptogenesis

May 15th 2024,
4th EuCAPT Annual Symposium,
CERN, Geneva, Switzerland

Juraj Klarić

University of Zagreb
Universiteit van Amsterdam
Nikhef

Evidence for the Baryon Asymmetryof the Universe

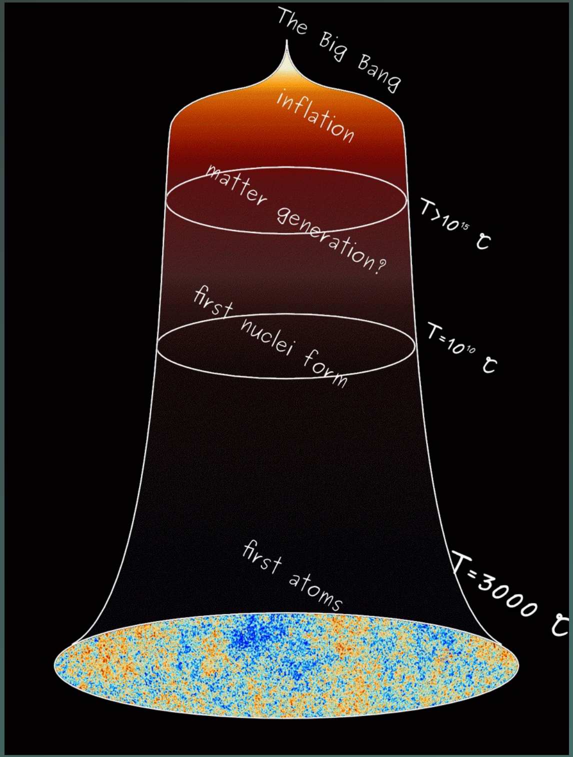


Animation by [Wayne Hu]

Figure from [PDG review]

- Our immediate surroundings is made out of matter
- Key observational evidence coming from the *Cosmic Microwave Background*
  - The baryon/photon ratio changes the ratio of the odd and even peaks
- Complementary evidence from *Big Bang Nucleosynthesis*

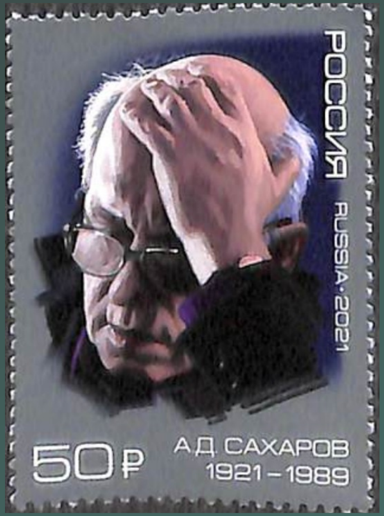
Where did the asymmetry come from?



- Was it always there?
  - Not compatible with inflation
  - Pre-inflationary relics are exponentially diluted
- It was generated through some process in the early Universe?

The Sakharov Conditions

In the SM?



Any baryogenesis mechanism needs to satisfy the three [Sakharov '67] conditions:

I) Baryon Number Violation

- **Sphaleron processes** ✓

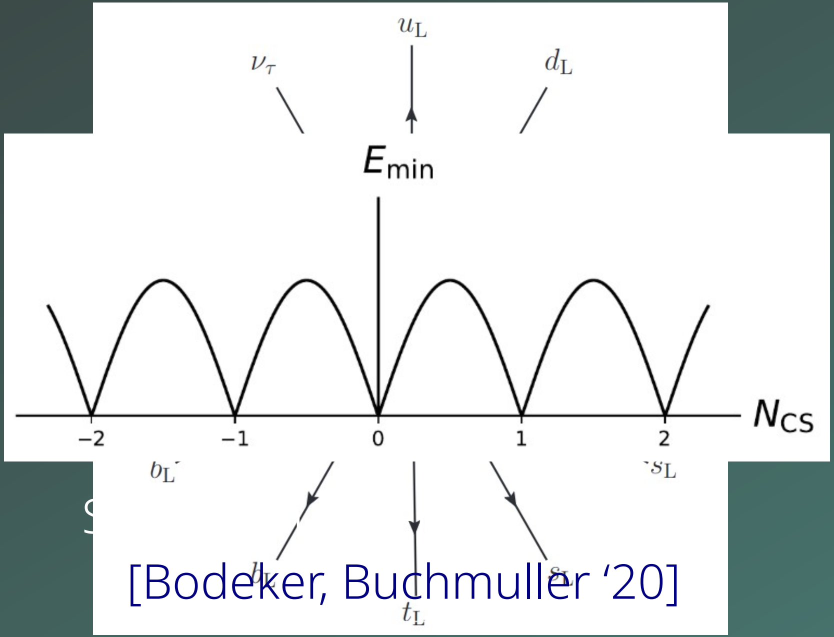
II) C and CP violation

- CP violation in the CKM matrix? ✗

III) Deviation from equilibrium

- **Phase transition (crossover)** ✗

Sphalerons?



[Bodeker, Buchmuller '20]

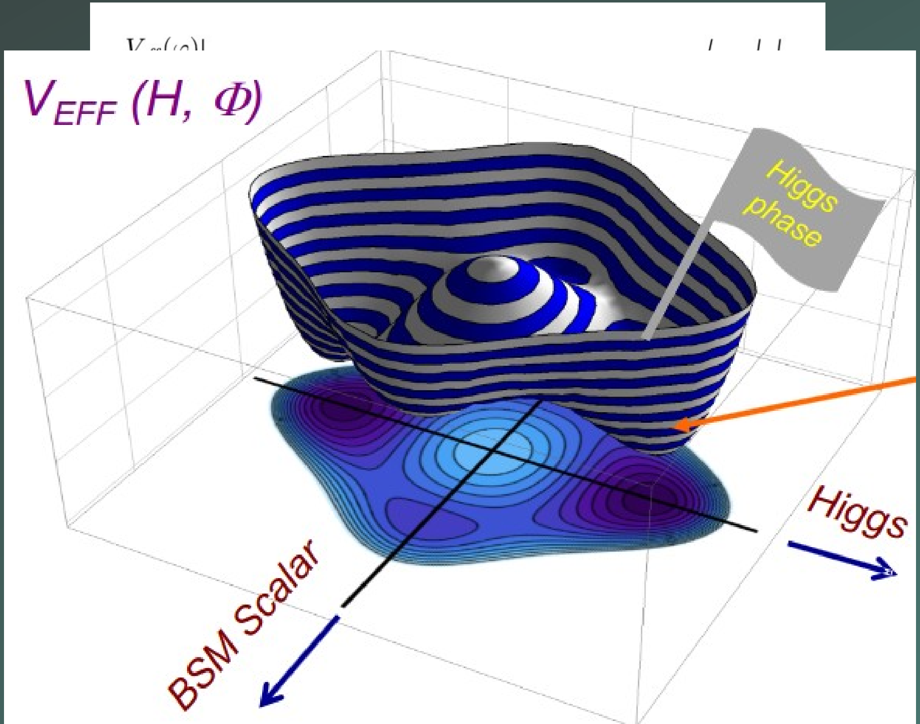
Weak Sphaleron, Fig. from Garbrecht '18

- **Standard model** processes that conserve ***B-L***, but violate ***B+L*** by **six units**
  ['t Hooft '76]
- Exponentially suppressed for ***T=0***
  (practically unobservable in terrestrial experiments)
- Unsuppressed at **high temperatures *T*> *130* GeV**
  [Kuzmin,Rubakov, Shaposhnikov '85]

Can we use this to generate the BAU?

Electroweak Baryogenesis (EWBG)

The EW phase transition



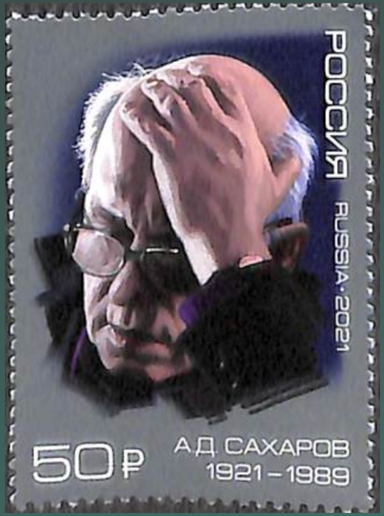
temperature,

Fig. from [Bodeker, Buchmuller '20]

Fig. by [Ramsey-Musolf]

- In EWBG ***the 1st order phase transition*** provides the deviation from equilibrium
- We have two phases:
  - Symmetric phase $\langle\varphi\rangle = 0$
  - Broken phase $\langle\varphi\rangle \neq 0$
- For ***m_H* > 70 GeV**, this transition is a **crossover** instead!
  [Buchmuller & Philippsen '94, Kajantie et. al. '96]
- 1st order P.T. still possible in extensions of the SM!
  - e.g. a two-step P.T.

The Sakharov Conditions



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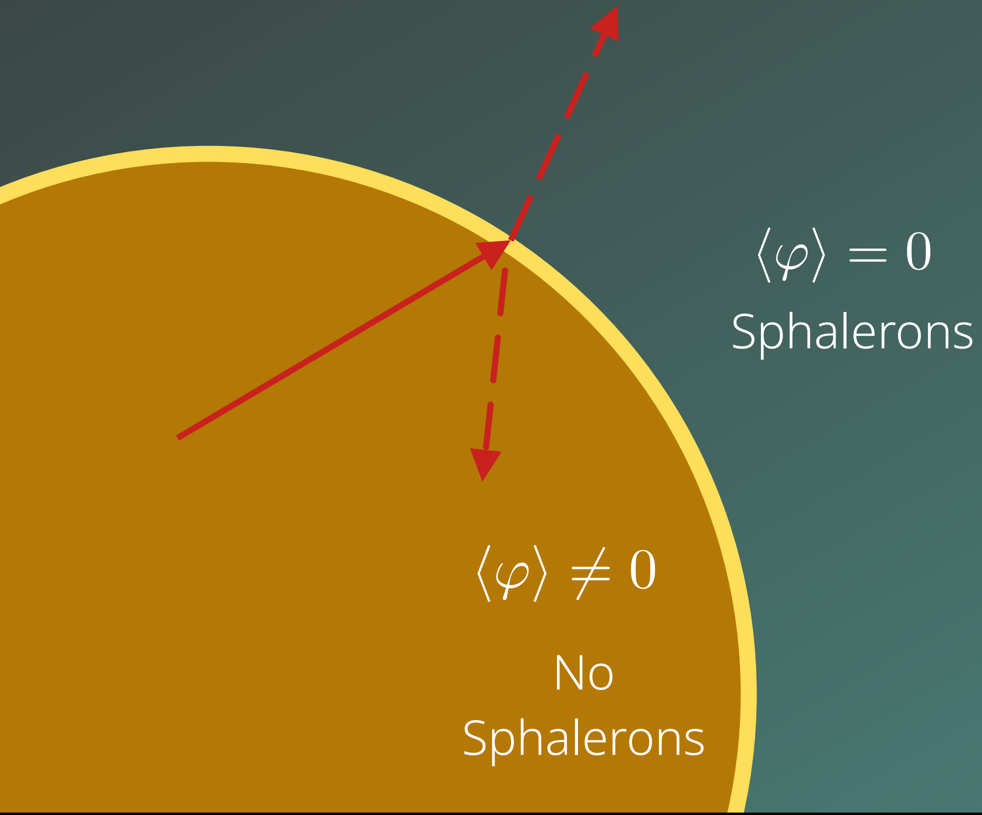
III) Deviation from equilibrium

- **1st order Phase Transition** ✓

Asymmetry generation in EWBG



- For a strongly 1st order P.T. bubbles of true vacuum nucleate as the Universe is cooling down
- As the bubble wall expands **CP-violating** interactions can lead to a spin separation:
  - Different transmission/reflection for particles and antiparticles
  - Sphaleron processes outside the bubble wash-out any asymmetry
  - The asymmetry inside the bubble survives

CP violating source

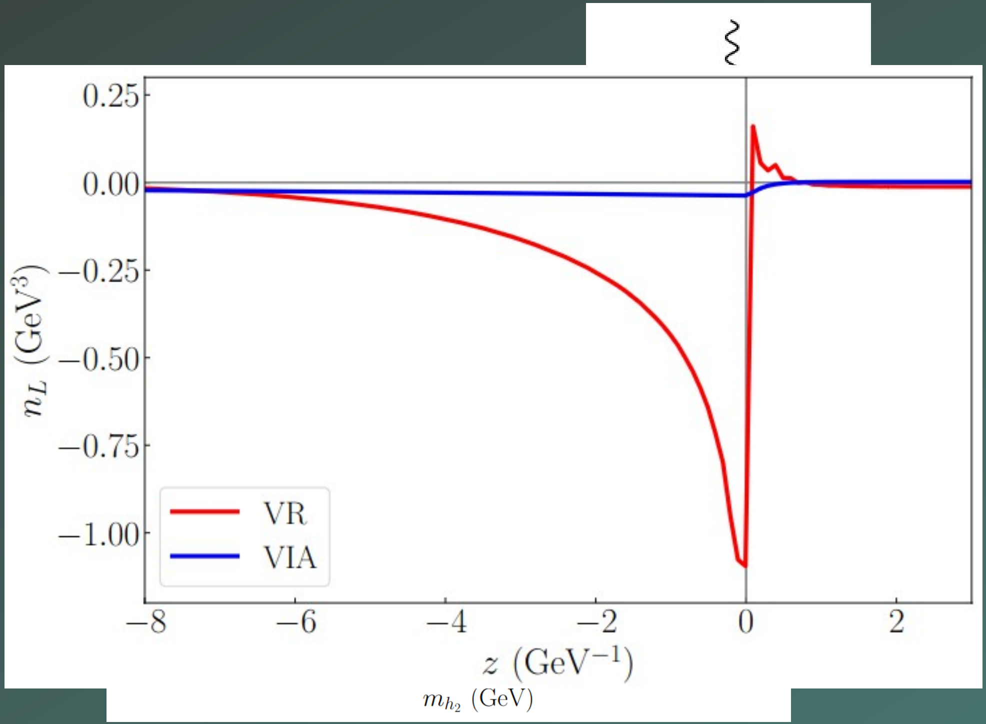


Fig. From [Li et. al '24]

- The question of CP violation is a difficult non-equilibrium QFT problem
- The full equations often untractable – we rely on controlled **approximations** to estimate the CP asymmetry:
  - Different computations can lead to different asymmetries – improved understanding is needed
- Simplest CPV sources should also lead to electron **Electric Dipole Moments**
- **Depending on the CPV source could already be excluded!**

The Sakharov Conditions

Any baryogenesis mechanism needs to satisfy the three [Sakharov '67] conditions:

I) Baryon Number Violation

- **Sphaleron processes** ✓

II) C and CP violation

- BSM CP violation ✓

III) Deviation from equilibrium

- **1st order Phase Transition** ✓

EWBG wishlist

- Modified Higgs potential:
  - **Collider target below 1 TeV!**
- Fast estimates of the **bubble nucleation rates**
- CP violating source terms:
  - Probes in **Electric Dipole Moments**
- Bubble wall velocities:
  - Connection to **Primordial Gravitational Waves**?

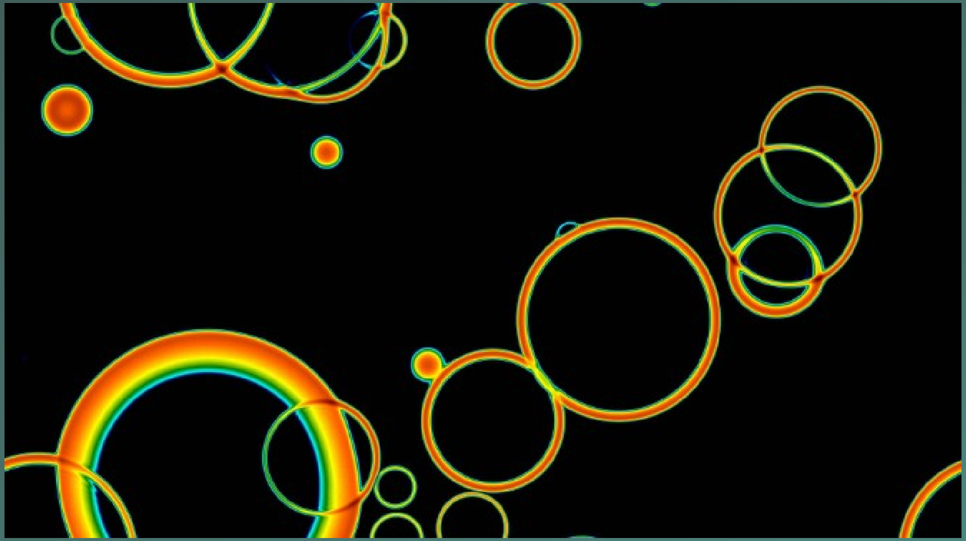
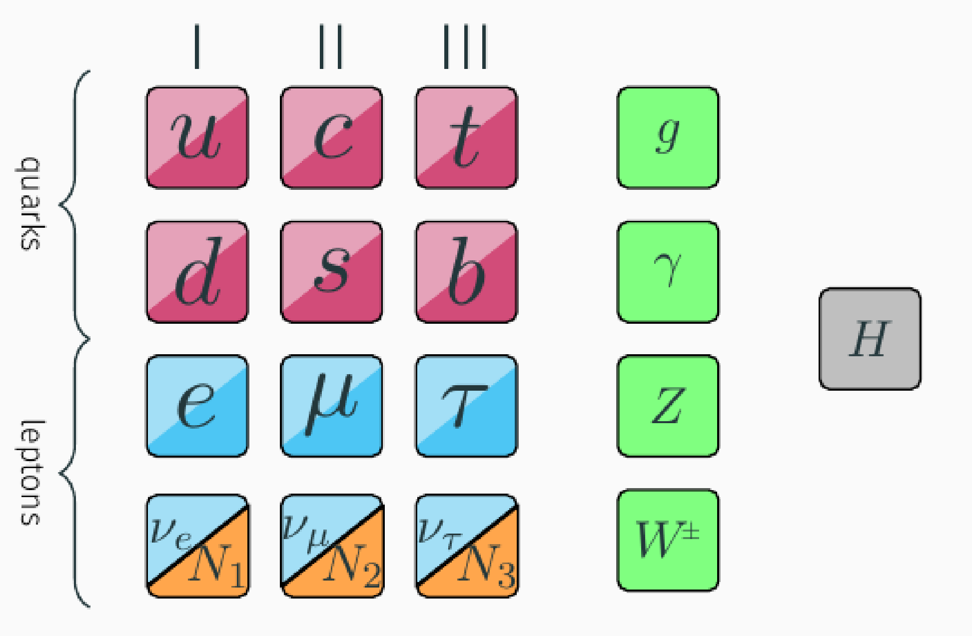


Fig. From [D. Weir '19]

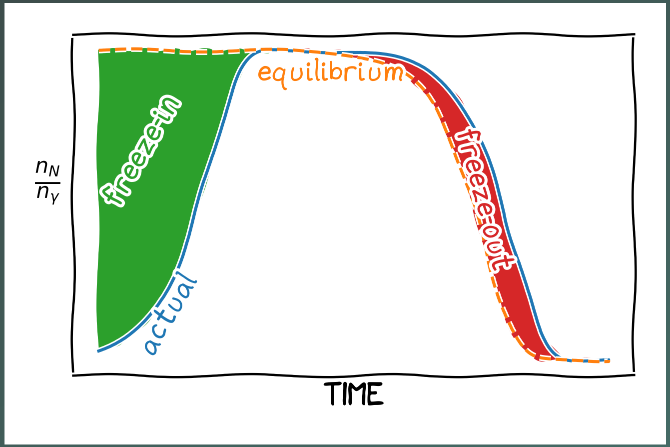
Leptogenesis

Can we generate a Lepton asymmetry instead?

- Neutrino masses are one of the best signs for physics beyond the SM
- Adding right-handed neutrinos is one of the easiest ways to generate the light neutrino masses
- The RHN decays can lead to a lepton asymmetry
- The lepton asymmetry is converted to a BAU through sphalerons
- This process is known as leptogenesis [Fukugita/Yanagida '86]



The Sakharov Conditions



Any baryogenesis mechanism needs to satisfy the three [Sakharov '67] conditions:

I) Baryon Number Violation

- **Sphaleron processes** ✓

II) C and CP violation

- CP violation in RHN decays and oscillations ✓

III) Deviation from equilibrium

- **Production and decays of RHNs** ✓

What is the mass scale of the right-handed neutrinos?

The see-saw Lagrangian

$$\mathcal{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

The light neutrino masses

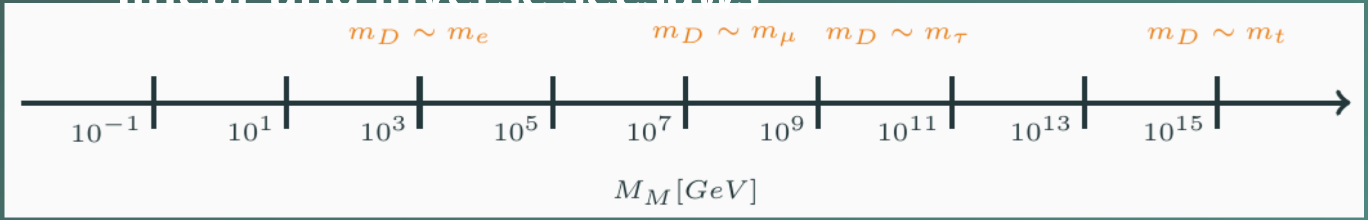
$$m_\nu = -m_D M_M^{-1} m_D^T$$

Mohapatra ’93
Mohapatra/Valle ’86
Bernabeu/Santamaria/Vidal/Mendez/Valle ’86
Gavela/Hambye/Hernandez/Hernandez ’09
Branco/Grimus/Lavoura ’89
Malinsky/Romao/Lavoura ’89

Low-scale linear and inverse seesaws

Minkowski ’77
Gell-Mann/Ramond/Slansky ’79
Mohapatra/Senjanović ’80
Yanagida ’79
Schechter/Valle ’80

Canonical type-I seesaw



Can leptogenesis provide more information?

Sphaleron freeze-out

Davidson-Ibarra '02

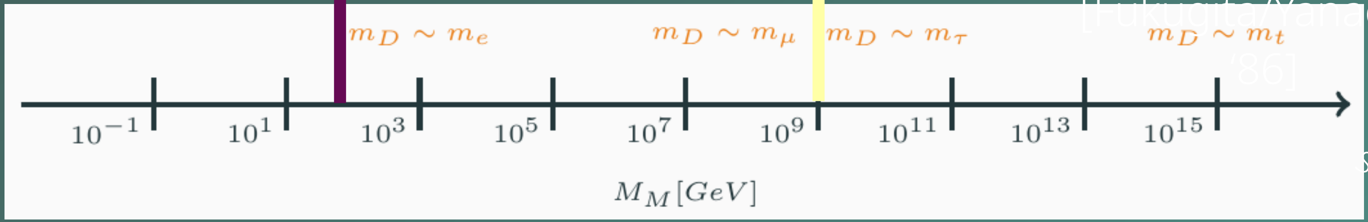
Low-scale leptogenesis

Leptogenesis via oscillations
[Akhmedov/Rubakov/Smirnov '98]
[Asaka/Shaposhnikov '05]

Resonant leptogenesis
[Liu/Segre '93]
[Pilaftsis '97]
[Pilaftsis/Underwood '04]

Flavoured leptogenesis
[Endoh et. al. '03]
[Pilaftsis/Underwood '05]
[Abada et. al. '06]
[Nir et. al. '06]

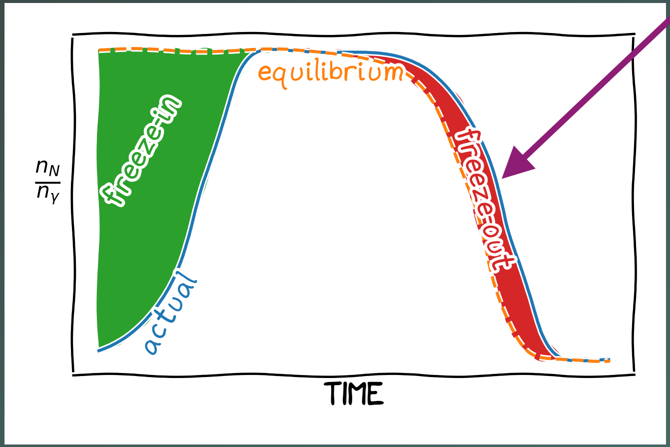
Thermal leptogenesis
[Fukugita/Yanagida '86]



More interesting scenarios in the posters of Ansh Bhatnagar, Martina Cataldi and Károly Seller

Thermal leptogenesis

- the BAU is mainly produced in the decays of RHN
- as the universe expands, cools down to T ≤ M the RHN become non-relativistic and begin to decay



The lepton asymmetries follow the equation:

$$\frac{dY_{\ell_a}}{dz} = -\epsilon_a \frac{\Gamma_N}{Hz}(Y_N - Y_N^{\mathrm{eq}}) - W_{ab} Y_{\ell_b}$$

The key quantity determining the BAU is the decay asymmetry:

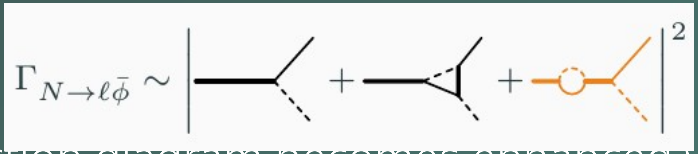
$$\epsilon_a \equiv \frac{\Gamma_{N\to l_a} - \Gamma_{N\to \bar{l}_a}}{\Gamma_{N\to l_a} + \Gamma_{N\to \bar{l}_a}}$$

Resonant leptogenesis

- For hierarchical neutrinos, the decay asymmetry is limited by the Davidson-Ibarra bound:

$$|\epsilon| \lesssim \frac{3 M_1 m_\nu}{8\pi v^2}$$

- However, if have a careful look at the diagrams:



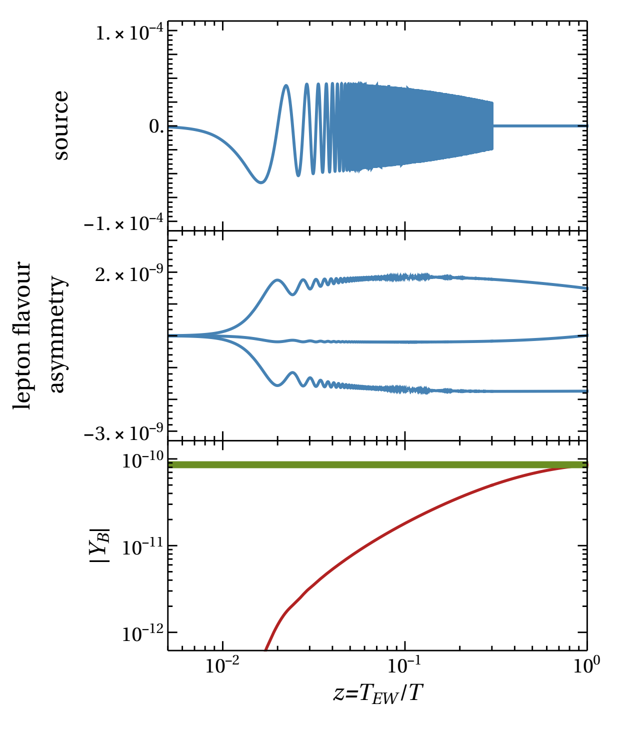
- we find that the wave-function diagram becomes enhanced when $M_2 \to M_1$

$$\epsilon = \frac{1}{8\pi} \frac{\mathrm{Im}(F^\dagger F)^2_{12}}{(F^\dagger F)_{11}} \frac{M_1 M_2}{M_1^2 - M_2^2}$$

[Liu/Segrè/Flanz/Paschos/Sarkar/Weiss/Covi/Roulet/Vissani/Pilaftsis/Underwood/Buchmüller/Plumacher...]

This enhancement is known as **resonant leptogenesis**!

Leptogenesis via oscillations



- The lepton asymmetry is produced during RHN production (freeze-in) instead of decays
- The RHN interaction basis and mass basis are mismatched
- The RHNs begin to oscillate, and build up CP odd correlations
- Further scatterings lead to a lepton flavor asymmetry
- The lepton flavor asymmetry is converted t a lepton number asymmetry through washout effects

How to describe this process?

System of kinetic equations

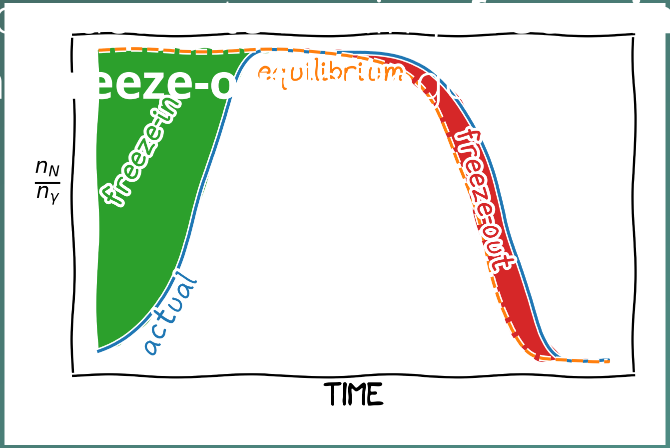
$$i\frac{dn_{\Delta\alpha}}{dt} = -2i\frac{\mu_\alpha}{T}\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}\left[\Gamma_\alpha\right] f_N\left(1-f_N\right) + i\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}\left[\tilde{\Gamma}_\alpha\left(\bar{\rho}_N-\rho_N\right)\right],$$

$$i\frac{d\rho_N}{dt} = \left[H_N,\rho_N\right] - \frac{i}{2}\left\{\Gamma,\rho_N-\rho_N^{eq}\right\} - \frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N\left(1-f_N\right)\right],$$

$$i\frac{d\bar{\rho}_N}{dt} = -\left[H_N,\bar{\rho}_N\right] - \frac{i}{2}\left\{\Gamma,\bar{\rho}_N-\rho_N^{eq}\right\} + \frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N\left(1-f_N\right)\right],$$

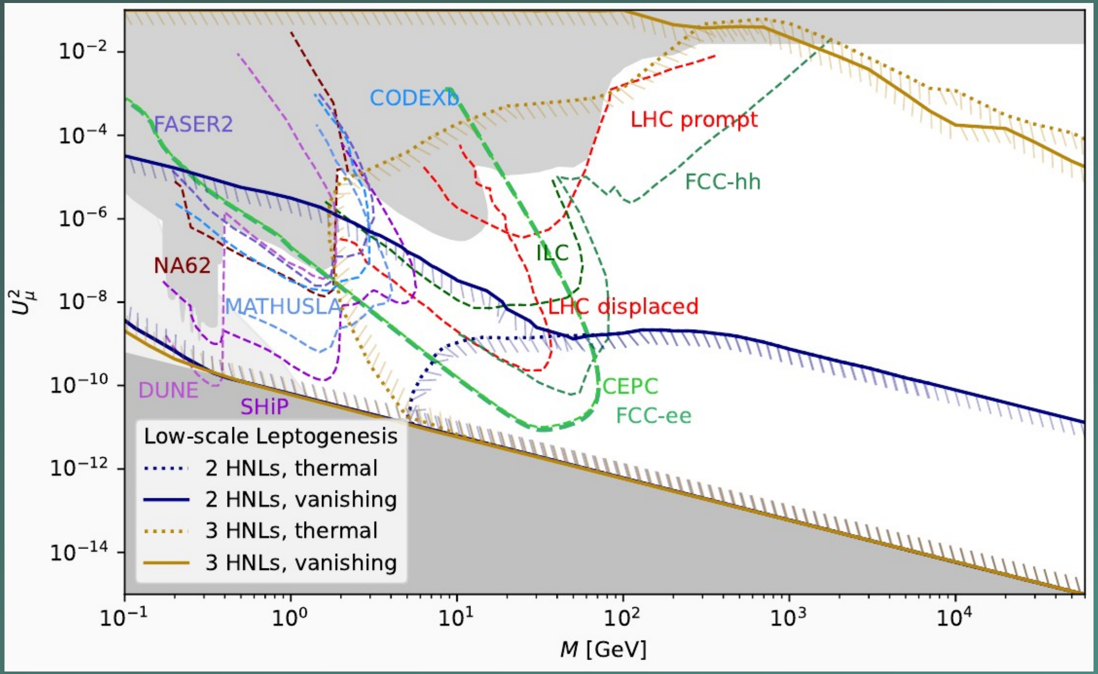
- Equations used to describe resonant leptogenesis and leptogenesis via oscillations are quite similar
- Both can be shown as specific limits of a generalized set of equations
- Other leptogenesis may require further care

- Physically, the **same resonant enhancement** present for in both types of low scale leptogenesis
- Main difference is in the **deviation from equilibrium**
- Mo … an … **eeze-o**



The parameter space of leptogenesis

- With 2 RHNs leptogenesis is possible for ***all masses above 100 MeV***
- Leptogenesis is possible in the ***entire experimentally accessible parameter space*** for 3 RHNs
- Large overlap between freeze-in and freeze-out leptogeneses



Conclusions

- Baryogenesis and leptogenesis are testable mechanisms to generate the observed BAU
- Conclusive tests may require a combination of different experiments and observations:
  - High energy experiments
  - Gravitational wave observations
  - Precision observables (EDMs, neutrinoless double beta decay, LFV…)
- I only covered a small portion of baryogenesis mechanisms: there are many exciting options on the table