The outline of this talk is

One of the great mysteries of our universe is the observed matter (protons+neutrons) antimatter asymmetry. Since there is good evidence that the universe is mostly made of matter (and no antimatter) the baryon density corresponds to the cosmological matter-antimatter asymmetry. This number is determined from consistency with BBN data as (PDG):

\[ \eta_{BBN} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} = 6.05(7) \times 10^{-10} \]

Why does this ratio have this value? In the SCM starting from an initial symmetric state at high temperatures (after inflation) one would expect a much smaller baryon asymmetry.
There are then two options within the SCM

1. A small baryon-antibaryon asymmetry has to be imposed **by hand** as an **initial condition** (not very satisfactory)

2. Some **dynamical mechanism** has produced a tiny baryon-antibaryon asymmetry in the early universe leading, after \( p\bar{p} \) annihilations, to the required baryon asymmetry (advised)

It was suggested by Sakharov in 1967 \(^1\) that a tiny \( n_{\Delta B} \) might have been produced in the early universe leading to \( \eta_{BBN} \). The three necessary ingredients for baryogenesis are:

**Sakharov conditions**

- B-violation
- C and CP violation
- Departure from thermal equilibrium. The out-of-equilibrium conditions are present e.g. in the bubble wall in a **first order phase transition**, in particular for **ElectroWeak BaryoGenesis** (EWBG)

\(^1\) A.D. Sakharov, JETPL 91B (1967) 24
Two conditions for EWBG

1. Baryon asymmetry has to be generated

If there is not enough \( CP \)-violation the mechanism for generating the BAU does not work, or does not generate enough baryon asymmetry

2. Baryon asymmetry should not be washed out

If the phase transition is not strongly enough first order any previously generated BAU is erased by sphalerons in the symmetric phase
**EWBG in the Standard Model**

- Saharov’s conditions are fulfilled in the Standard Model
- In a system at finite temperature baryon number can be sizeably violated by sphaleron solutions

**Sphaleron rate at \( T > T_c \): in the symmetric phase**

The rate of baryon violation per unit time and unit volume \( \Gamma \) does not contain any exponential Boltzmann factor

\[
\Gamma = k (\alpha_W T)^4, \quad 0.1 \lesssim k \lesssim 1.0
\]

**Sphaleron rate at \( T < T_c \): in the broken phase**

The rate per unit time and unit volume for fluctuations between neighboring minima contains a Boltzmann suppression \( \zeta(T) = E_{\text{sph}}(T)/T \)

\[
\Gamma \sim 2.8 \times 10^5 T^4 \left( \frac{\alpha_W}{4\pi} \right)^4 \kappa \frac{\zeta^7}{B^7} e^{-\zeta}, \quad 10^{-4} \lesssim \kappa \lesssim 10^{-1}
\]
Out of equilibrium conditions

The out of equilibrium condition can be achieved, if the phase transition is strong enough first order, in the bubble walls. In that case the B-violating interactions are out of equilibrium in the bubble walls and a net B-number can be generated during the phase transition.

How strong should the phase transition be to not erase the baryon asymmetry? ⇔ How much out of equilibrium the sphaleron should be?

- The condition for the sphalerons to be out of equilibrium

\[ \frac{E_{\text{sph}}(T_c)}{T_c} \gtrsim 45 \]

- This translates into a constraint for the value of the Higgs field \( \phi \)

\[ \frac{\phi(T_c)}{T_c} \gtrsim 1 \]
The SM fails quantitatively to fulfill the out of equilibrium & CPV conditions

**CP violation**

The SM contains the $O(1)$ CP-violating CKM phase required for EWBG

But it was soon realized $^a$ that the effect was suppressed by the Jarlskog invariant and

$$\frac{n_B}{n_{\gamma}} < 6 \times 10^{-27} \implies \text{BSM}$$

Extra CP Violating phases!!!

$^a$M.B. Gavela et al., hep-ph/9312215

Extra stuff to strengthen PhT!!!

$\phi_c / T_c$ Vs $m_H / \text{GeV}$ @ one-loop
As we have seen we need extra CP-violating phases to generate baryon asymmetry. They will also generate EDM which are severely constrained by experimental data. The most constraining ones are for the electron and the neutron:

\[ |d_e| < 1.1 \times 10^{-29} \, e \cdot cm \quad (90\% CL), \quad |d_n| < 3.0 \times 10^{-26} \, e \cdot cm \quad (90\% CL) \]

They generically imply \( \sim 10^{-3} \) phases. The statement of the SUSY CP-problem and it is barely at odd with EWBG. For \( O(1) \) phases, e.g. in the MSSM, the first and second generation squarks must be heavy enough (\( \sim 10 \) TeV): pay attention to two-loop contribution to EDM from charginos and neutralinos.
Two loop (Barr-Zee type) diagrams may be competitive or even dominant $^2$.

\[\text{Diagram (a)}\]

\[\text{Diagram (b)}\]

\[\text{Diagram (c)}\]

\[\text{Diagram (d)}\]

The simplest solution out of this problem is to have models with CP violated in a Dark sector. The schematic picture of the model we propose contains a dark sector with Dark Matter, a dark $U(1)'$ gauge boson $Z'$ and CP violation. Main challenge: to find an efficient mechanism to transfer the CP violation from the dark sector to the visible sector in the early universe, while still keeping contributions to EDMs sufficiently suppressed today.
A model with dark CPV and gauged lepton number

We consider an extension of the SM with gauged lepton 
\[ \ell \equiv L_e + L_\mu + L_\tau \text{ number: } U(1)_\ell \]

Additional fermions (anomalons) should be introduced for anomaly cancellation, \( q \in \mathbb{R} \)

<table>
<thead>
<tr>
<th>Particle</th>
<th>( SU(3)_c )</th>
<th>( SU(2)_L )</th>
<th>( U(1)_Y )</th>
<th>( U(1)_\ell )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_R' )</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>( L'_L = (\nu'_L, e'_L)^T )</td>
<td>1</td>
<td>2</td>
<td>-1/2</td>
<td>q</td>
</tr>
<tr>
<td>( e'_R )</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>q</td>
</tr>
<tr>
<td>( \chi_R )</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>q</td>
</tr>
<tr>
<td>( L''_R = (\nu''_R, e''_R)^T )</td>
<td>1</td>
<td>2</td>
<td>-1/2</td>
<td>q + N_g</td>
</tr>
<tr>
<td>( e''_L )</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>q + N_g</td>
</tr>
<tr>
<td>( \chi_L )</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>q + N_g</td>
</tr>
</tbody>
</table>

Fermion \( \chi \) will be Dark Matter

---

\[ U(1)_\ell \] is spontaneously broken by a Higgs VEV, \( \langle \Phi \rangle = v_\Phi \), with \( \ell_\Phi = N_g = 3 \), at the (multi)TeV scale

- Anomalons get spontaneous breaking masses by the Yukawa interactions

\[
(c_L \bar{L}'_R L'_L + c_e \bar{e}'_L e'_R + c_\chi \bar{\chi} L \chi_R) \Phi + \text{h.c.}
\]

- Considering \( c_L \sim c_e \sim \mathcal{O}(1) \), the charged anomalons \( L'_L, L''_R, e''_L, s'_R \) are integrated out at scales (and temperatures) of order \( v_\Phi \)

- For small \( g' \) and \( c_\chi \), \( Z' \) and \( \chi \) have masses around the EW scale

- For EWBG we need another scalar \( S \), with \( \ell_S = N_g \), coupled to the Higgs portal and the DM

\[
\mathcal{L} = -\lambda_{SH} |S|^2 |H|^2 + \bar{\chi} L (m_0 + \lambda_c S) \chi_R + \text{h.c.}
\]

making the EW phase transition first order

- The mass of \( \chi \) changes with the \( S \) field profile during the electroweak phase transition. If the relative phase between \( m_0 \) and \( \lambda_c S \) is physical, it will serve as a source of CP violation in our EWBG
The global picture for phase transition is as follows

1. At very high temperatures, all symmetries are restored.
2. As the universe cools down to the temperature $T_\Phi \sim v_\Phi$, the $\Phi$ field acquires its VEV, $\langle \Phi \rangle = v_\Phi$, and the lepton number symmetry is broken. The nature of this phase transition is not relevant.
3. As the universe further cools down to a temperature $T_S$ not far above the electroweak scale $T_{EW}$, the $S$ field first develops a VEV, $\langle S \rangle \neq 0$, when its mass squared term (including the thermal corrections) becomes negative, while the Higgs VEV remains zero, $\langle H \rangle = 0$. The nature of this transition is not relevant.
4. At the critical temperature near the electroweak scale, $T_c$, a new minimum of the potential with $\langle H \rangle \neq 0, \langle S \rangle \approx 0$ emerges that turns into the true minimum. This process must involve a first-order phase transition requiring the presence of a barrier between both minima. The universe tunnels from one vacuum to the other via bubbles.
At high temperatures, there are thermal corrections, \( a_H T^2 |H|^2 \) and \( a_S T^2 |S|^2 \). Thus, at very large \( T \), the potential will be minimized for \( \langle H \rangle = \langle S \rangle = 0 \) (steps 1 and 2).

Given that the Higgs field couples to more degrees of freedom than \( S \), it follows that \( a_H > a_S \), and it is always possible to find a temperature where the Higgs quadratic term is positive, while the \( S \) quadratic term is negative (step 3).

At lower temperatures, however, the Higgs quadratic term will also turn negative.
We have considered a potential as

\[ V(H, S) = \lambda_H(|H|^2 - v^2)^2 + \lambda_S(|S|^2 - v_S^2)^2 + \lambda_{SH}|S|^2|H|^2 + \mu_S^2 S^2 \]

The physical source of CP violation arises from the \( \chi \) mass term

\[ M_\chi = m_0 + \lambda e^{i\theta}|S|, \quad \theta = \text{const} \]

During the first-order electroweak phase transition, in the presence of a bubble wall, the magnitude of \( |S| \) is space-time dependent, hence having used the freedom to make \( m_0 \) real, the phase of \( M_\chi \) is not removable.

This phase provides the key source of CP violation for baryogenesis.
The particle chiral asymmetries in the dark sector are

\[ \xi_{\chi_{L,R}}(z) = \frac{3}{T_c^3} \left( n_{\chi_{L,R}} - n_{\chi_{L,R}}^c \right), \quad \xi_{\chi_{L,R}} \equiv \frac{\mu_{\chi_{L,R}}}{T_c} \]

The chiral asymmetries diffuse with the diffusion equation

\[ -D \xi''_{\chi_L}(z) - v_\omega \xi'_{\chi_L}(z) + \Gamma_m [\xi_{\chi_L}(z) - \xi_{\chi_R}(z)] = S_{\text{CPV}} \]

The diffusion constant \( D \) is given by \( D = \langle v^2 \rangle / (3\Gamma_m) \), with \( \Gamma_m \sim \lambda^2 T_c / (4\pi) \), \( v \) is the particle velocity in the bubble wall rest frame, and \( \langle \rangle \) is the thermal average over the Fermi-Dirac distribution function in the rest frame of the bubble wall.
The CP violating source term is \( E^2 = p^2 + |M_\chi(z)|^2 \)

\[
S_{CPV} = \frac{v_\omega}{\Gamma m T_c} \left\langle \frac{v_z}{2E^2} \right\rangle \frac{m_0 v_S \lambda \left[ -2 + \cosh \left( \frac{2z}{L_\omega} \right) \right] \sin \theta}{L_\omega^3 \cosh^4 \left( \frac{z}{L_\omega} \right)}
\]

\[10^5 \xi_{\chi L} \]

\[ z/L_\omega \]

---

\(^4\) J. Cline et al., hep-ph/0006119
Unlike in usual EWBG scenarios, here the chiral asymmetry is generated in the dark sector through the $\chi$ particle, which is an $SU(2)_L$ singlet and thus does not couple to electroweak sphalerons.

However thanks to the leptonic $Z'$ portal, which couples to both $\chi$ and the SM leptons, the CP violating effect in the dark sector can be transferred to the observable sector.

As $\chi_L$ and $\chi_R$ carry different $U(1)_\ell$ charges ($q + N_g$ and $q$ respectively), the above chiral asymmetries imply a net $U(1)_\ell$ charge density near the bubble wall as,

$$\rho_\ell(z) = (q + N_g) [n_{\chi_L} - n_{\chi^c_L}] + q [n_{\chi_R} - n_{\chi^c_R}] = \frac{1}{3} N_g T_c^3 \xi_{\chi_L}(z)$$

The existence of this net $U(1)_\ell$ charge density yields a Coulomb background of the $Z'$ potential, $\langle Z'_0 \rangle$

$$\langle Z'_0(z) \rangle = \frac{g'_1}{2 M_{Z'}} \int_{-\infty}^{\infty} dz_1 \ \rho_\ell(z_1) \ \exp [-M_{Z'} |z - z_1|]$$
As $Z'_0$ couples to the leptonic currents $Z'_0(\bar{L} L \gamma^0 + e_R \gamma^0 e)$ its background acts as a \textit{spontaneous baryogenesis} mechanism and generates \textit{chemical potentials}, i.e. thermal equilibrium asymmetry, for SM leptons

\[
\mu_{L_L}(z) = \mu_{\ell_R}(z) = g' \langle Z'_0(z) \rangle, \quad \Delta n^{\text{EQ}}_{L_L}(z) = \frac{2g' N g T_c^2}{3} \langle Z'_0(z) \rangle
\]
In the presence of EW sphaleron processes

\[ \Delta n_B = \frac{\Gamma_0}{\nu_\omega} \int_0^\infty dz \Delta n_{EQ}^L(z) e^{-\Gamma_0 z/\nu_\omega} \]

where \( \Gamma_0 \approx 120 \alpha_w^5 T_c \approx 10^{-6} T_c \) is the sphaleron rate in the unbroken phase, an asymmetry is generated.

We have scanned over all free parameters in the range

\[ (M_{Z'}, m_0) \in (10^{-3}, 10^3) \text{GeV}, \quad (\nu_S, T_c) \in (100, 500) \text{GeV} \]
\[ \lambda \in (10^{-2}, 1), \quad g' \in (10^{-6}, 0.1), \quad \theta \in (-\pi/2, \pi/2), \]
\[ L_w \in (1/T_c, 10/T_c), \quad \nu_\omega \in (0.05, 0.5) \]
\[ M_{Z'} < 2m_0 \]

The case \( M_{Z'} > 2m_0 \) is practically excluded by the various constraints.
The observed baryon asymmetry of the universe is covered by the blue points, in the $g'$ versus $M_{Z'}$ plane.
Z′ couples to the SM charged leptons and neutrinos. Directly searched for at $e^+e^-$ colliders, such as LEP, and BaBar, as well as at electron beam dump experiments, and neutrino experiments that are sensitive to neutrino-electron interactions (such as TEXONO).

At the loop level it can contribute to the anomalous magnetic moments of charged leptons $(g - 2)_\mu$, $(g - 2)_e$.

As Z′ couples to an anomalous current with respect to $SU(2)_L^2$ in the low energy theory, it makes important contributions to flavor-changing meson decays such as $K \rightarrow \pi Z'$ and $B \rightarrow KZ'$.

---

5 J.A. Dror et al., arXiv:1707.01503
Visibly decaying $Z'$

- $(g-2)_e$
- $(g-2)_\mu$
- LEP
- BABAR
- TEXONO
- Beam Dump

$M_Z$ (GeV)

$\nu_\Phi = 1\,\text{TeV}$
$\nu_\Phi = 10\,\text{TeV}$
$B \rightarrow K\mu\mu$
$K \rightarrow \pi\nu\nu$
Particle $\chi$ from the dark sector could be a dark matter candidate, since there is a $\mathbb{Z}_2$ symmetry in the Lagrangian ($\chi \rightarrow -\chi$) allowing it to be stable.

Obtaining the correct relic density for $\chi$ through this channel then requires $\lambda$ to lie within the window

$$\sqrt{\frac{m_0}{1.4 \text{ TeV}}} < \lambda < \sqrt{\frac{m_0}{1.0 \text{ TeV}}}$$
- **Direct detection** of dark matter in this model could occur through $Z'$ exchange.
- Because the $Z'$ is the gauge boson for lepton number, it does not directly couple to nucleons, implying that the dark matter-nucleon scattering should occur through loop of charged leptons which effectively act as a kinetic mixing $Z'_{\mu\nu}F^{\mu\nu}$.
- **Diagrams for direct detection** are
Band is consistent with thermal relic density. Magenta points are consistent with both the observed baryon asymmetry and the dark matter direct detection experiments. Blue points fail to pass direct detection.
A CP violating Higgs-$Z'$ operator, of the form $hZ'_{\mu\nu}\tilde{Z}'^{\mu\nu}$, at two loop level, is shown in the diagram below.

It generates an EDM for the electron at four loop $d_e \lesssim 10^{-30} \text{e} \cdot \text{cm}$, below experiment $d_{e}^{\text{exp}} < 1.1 \cdot 10^{-29} \text{e} \cdot \text{cm}$.
The scalar $S = r + ia$ decays into $Z'Z'$ via one-loop from the operators $rZ' \mu\nu Z' \mu\nu$, $rZ' \tilde{Z}' \mu\nu$, $aZ' Z' \mu\nu$, $aZ' Z' \tilde{Z}' \mu\nu$ from

$$\mathcal{L}_{\text{dark Yukawa}} = \lambda e^{i\theta} \bar{\chi} L \chi R S + h.c.$$ 

$$= \frac{r}{\sqrt{2}} \left( \lambda \cos \theta \bar{\chi} \chi + \lambda \sin \theta \bar{\chi} i \gamma_5 \chi \right) + \frac{a}{\sqrt{2}} \left( -\lambda \sin \theta \bar{\chi} \chi + \lambda \cos \theta \bar{\chi} i \gamma_5 \chi \right)$$

It is produced in pairs $rr$ and $aa$ via the Higgs portal interaction

$$\mathcal{L}_{HS} = -\lambda_{HS} |S|^2 |H|^2$$
The production cross section at the LHC

Quantitatively, \( \sigma_{gg \rightarrow rr,aa} \sim 10\lambda_{SH}^2 \) fb (\( \sim 0.1\lambda_{SH}^2 \) fb) for \( M_r, a \simeq 150 \) GeV (for \( M_r, a \simeq 300 \) GeV)

After the decays of the \( r \) (or \( a \)) scalars, the final state could contain as many as 4 pairs of charged leptons, a very striking signal

We find that the existing LHC data could already cover the region where the dark scalar (\( r \) or \( a \)) is lighter \( \sim 200 \) GeV for \( \lambda_{SH} \sim \mathcal{O}(1) \)
The role of the dark sector CP violation in our EWBG mechanism for the $U(1)_{\ell}$ model

1. CP is first violated in the dark sector, containing the $\chi_{L,R}$ fermions. Their mass term has an irreducible phase that becomes time-dependent during the first-order phase transition.

2. This time dependent CP violating mass generates particle chiral asymmetries for $\chi_{L,R}$ in the dark sector, which diffuse to the exterior of the bubble wall, where SM sphalerons are active.

3. $\chi_L$ and $\chi_R$ carry different $U(1)_{\ell}$ charges such that their chiral asymmetries generate a net $U(1)_{\ell}$ charge density near the wall, that yields a Coulomb background for $Z_0'$
4 Given that the gauge field $Z_0'$ couples to the SM leptons, it generates a chemical potential for the SM leptons

5 In the presence of sphaleron processes, active outside the bubble, the SM lepton number asymmetry is generated

7 As sphalerons preserve $B - L$, they can change the generated SM lepton number into baryon number. Hence, a baryon number asymmetry will be equally generated

8 Inside the bubbles the sphaleron processes are suppressed, and the baryon asymmetry generated at the phase transition is not washed out.
Phenomenological features

- The model has a candidate for **Dark Matter in the dark sector**, satisfying all direct detection bounds.
- As CP is violated in the dark sector, it contributes to the electron EDM at four loop, below present experimental limits and possibly with no signal in the next generation experiments.
- The lighter the $Z'$ the more weakly coupled it should be. Near future and prospective experiments: BELLE II, NA64 ($\mu$ mode), SHiP, Higgs factories, ...
- New extra scalar can be produced at the LHC with 8 charged leptons as the final state.
- The model belongs to a **wider class of models** as gauging $L_\mu + L_\tau$ ($N_g = 2$) or baryon number $B$ with similar (but not quite the same) phenomenology.
The case $U(1)_{L_\mu + L_\tau}$

CCFR (neutrino trident production), Borexino (solar neutrino-electron scattering)
The case $U(1)_B$

LHC hadronic widths of $\Upsilon$, $J/\Psi$