A model of dark energy and dark matter

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Current status

- Energy budget of the universe:

  With $\Omega_X = \rho_X/\rho_c$,

  - Baryons: $\Omega_{baryons} \sim 4\%$.
  - Dark Matter: $\Omega_{DM} \sim 23\%$.
  - Dark Energy: $\Omega_{DE} \sim 73\%$.

- Equation of state:

  $p = w\rho$

  Latest WMAP + SNLS (Supernova legacy Survey) gives

  $w = -0.97^{+0.07}_{-0.09}$

The ΛCDM scenario where the universe is dominated by a cosmological constant ($p = -\rho$) and cold dark matter gives the best fit to the data up to a redshift $z \sim 1$.

QUESTIONS:

- Can a dynamical model be built which can mimick the ΛCDM scenario at the present time?

- Other than dark energy, what are other consequences and how can we test them?

A model of Dark Energy: the False Vacuum

Questions:

- Could the universe be presently trapped in a false vacuum described by a potential of some scalar field (the acceleron) with $\rho_V \approx (3 \times 10^{-3}\, eV)^4$?

- What is this acceleron and what is the origin of its potential?

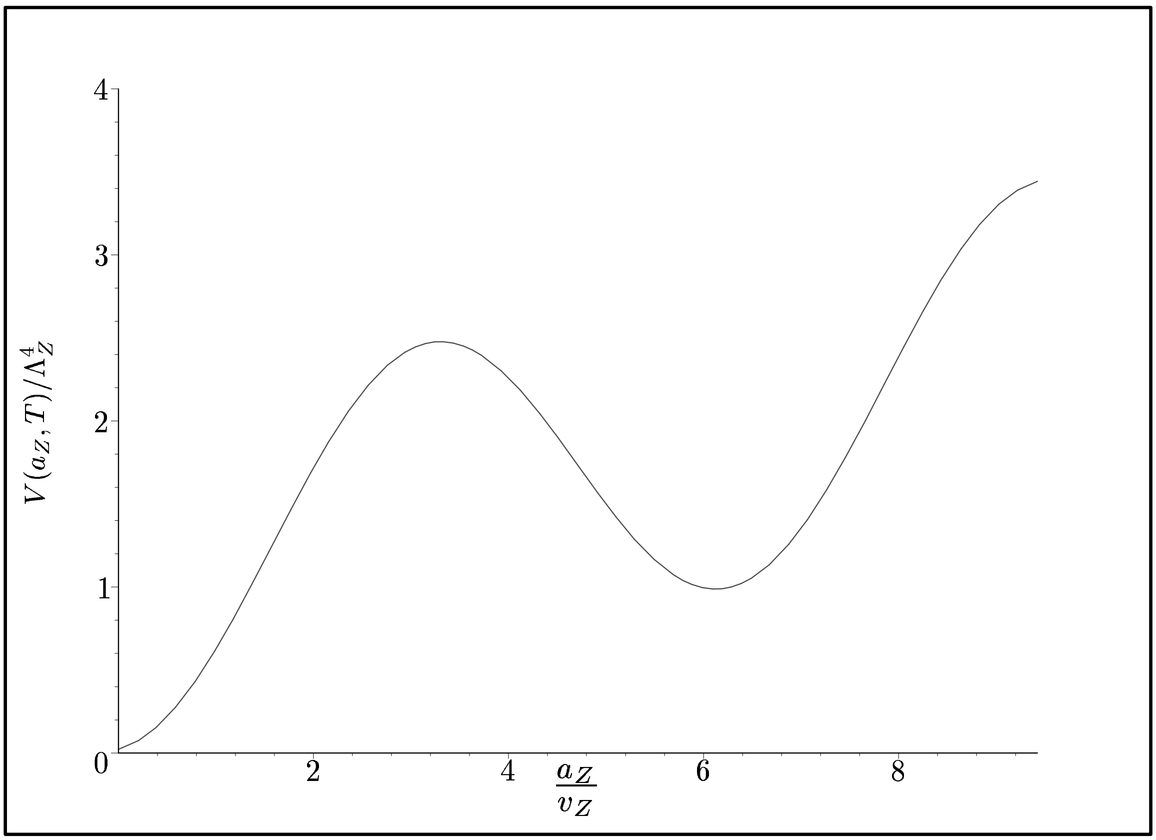
- How long will we be stuck in this false vacuum?

- What other particles are there in the model? What consequences do they have? Can they be detected?

- Model of hep-ph/0512281 (NPB747, 55 (2006)): The false vacuum.
  - Main assumption: there is a new (unbroken) gauge group $SU(2)_Z$ which becomes strong at $\Lambda_Z \sim 3\times 10^{-3}\,eV$. (More on it below.)
  - The acceleron, a_Z, is the pseudo-Nambu-Goldstone boson of a spontaneously broken global symmetry $U(1)_A^{(Z)}$ (very similar to the Peccei-Quinn symmetry).
  - a_Z is the imaginary part of a complex singlet scalar field $\phi_Z = v_Z \exp(ia_Z/v_Z) + \sigma_Z$ which couples to the $SU(2)_Z$ fermions $\psi_{1,2}^{(Z)} = (3,1)$ (under $SU(2)_Z \otimes SM$) as $\sum_i K_i\,\bar{\psi}_{L,i}^{(Z)}\,\psi_{R,i}^{(Z)}\,\phi_Z + h.c.$. This coupling includes the interaction between the acceleron a_Z and the CDM candidates $\psi_i^{(Z)}$.
  - The real part of ϕ_Z: σ_Z, could play the role of the inflaton associated with

a "low scale" inflation (in preparation with Eduard Masso and Gabriel Zsemsbinski).

– The potential of a_Z, $V(a_Z, T)$, is induced by the instantons of $SU(2)_Z$.



This potential has the form:

$$V(a_Z,T) = \Lambda_Z^4[1-\kappa(T)\cos\frac{a_Z}{v_Z}] + \kappa(T)\Lambda_Z^4\frac{a_Z}{2\pi\, v_Z}$$

where $\kappa(T) = 1$ at $T = 0$.

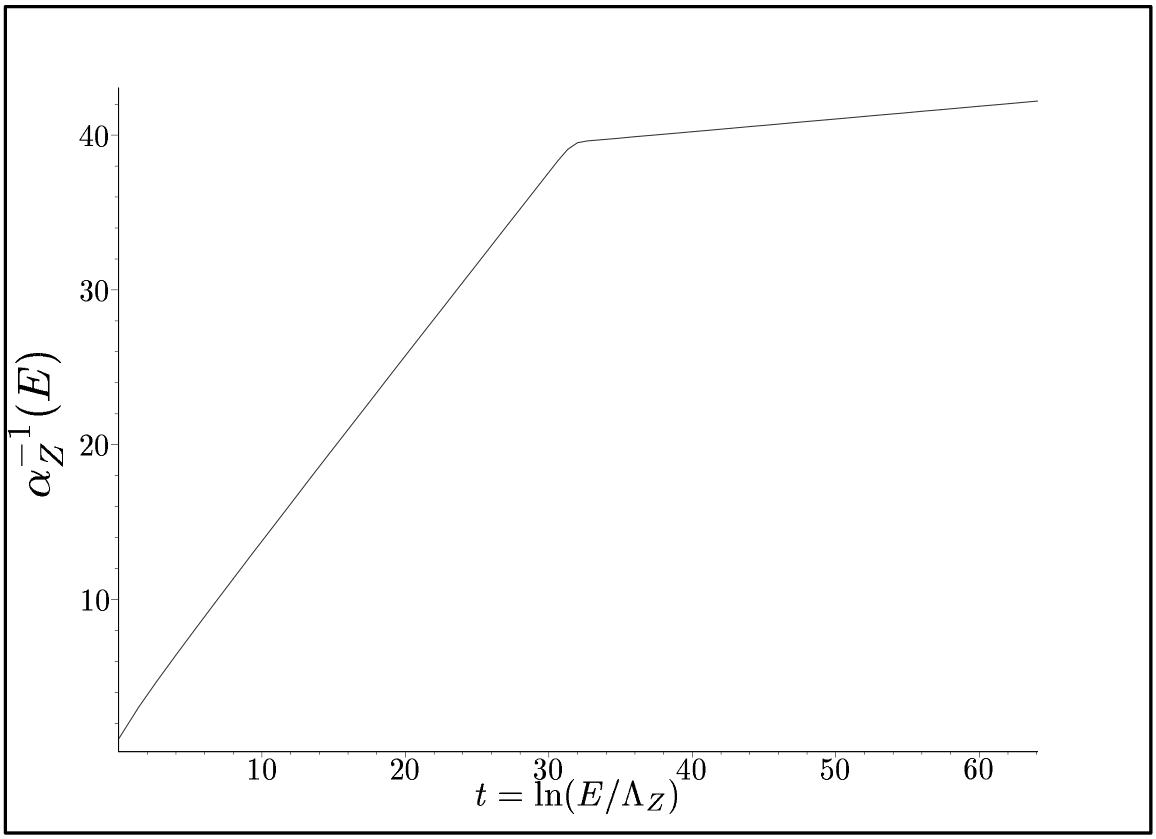
* The first term $\Lambda_Z^4[1-\kappa(T)\cos\frac{a_Z}{v_Z}]$ is induced by $SU(2)_Z$ instantons. Because of the remaining $Z(2)$ symmetry, there are two degenerate vacuua.

* The second term $\kappa(T)\Lambda_Z^4\frac{a_Z}{2\pi\, v_Z}$ is a soft breaking term which is linked to $SU(2)_Z$ fermion condensates (in preparation). This lifts the degeneracy of the two vacuua, one of which is a metastable (false) vacuum.

* For $T \gg \Lambda_Z$, $V(a_Z,T)$ is relatively flat. One also expects a_Z to hover around $O(v_Z)$. It is assumed that the universe is "stuck" in the false vacuum at $\langle a_Z\rangle = 2\pi v_Z$ for $T < \Lambda_Z$, with an energy density:

$$\rho_V = \Lambda_Z^4 \approx (3 \times 10^{-3}\, eV)^4$$

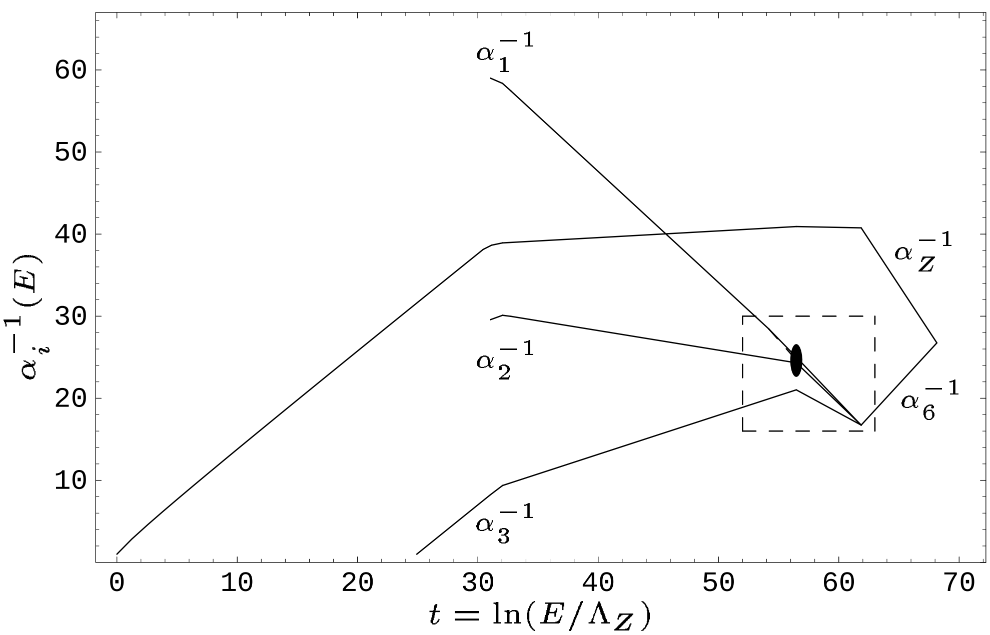
– Evolution of the $SU(2)_Z$ gauge coupling starting with a value of α_Z not too different from α_{SM} at high energies:



– Why is the $SU(2)_Z$ coupling α_Z of the order of α_{SM} at high energies?

$E_6 \rightarrow SU(2)_Z \otimes SU(6) \rightarrow SU(2)_Z \otimes SU(3)_c \otimes SU(3)_L \otimes U(1) \rightarrow SU(2)_Z \otimes SU(3)_c \otimes$

$SU(2)_L \otimes U(1)_Y \to SU(2)_Z \otimes SU(3)_c \otimes U(1)_{em}$ (in preparation with Paola Mosconi)



Implications of the DE model

- Various times:

  - History: ($H_0^{-1} = (0.96 \pm 0.04)^{-1}\, t_0$, $t_0 = 13 \pm 1.5 Gyr$)

    1) Age of the universe as a function of the redshift:

    $$t(z) = H_0^{-1} \int_z^\infty \frac{dz'}{(1+z')[\Omega_M(1+z')^3 + \Omega_{DE}]^{1/2}}$$

    assuming $\Omega_M + \Omega_{DE} = 1$. ($M$: baryonic + non-baryonic matter.)

    2) Age of the universe when $\rho_M \sim \rho_{vac}$:

    $z_{eq} \approx 0.33 \Rightarrow t_{eq} = 9.5 \pm 1.1\, Gyr$

    3) Age of the universe when the deceleration "stopped" and the acceleration "started" ($\ddot{a} = 0$):

    $z_a \sim 0.67 \Rightarrow t_a \approx 7.2 \pm 0.8\, Gyr$

– Transition from the false vacuum $a_Z = 2\pi v_Z$ to the true vacuum $a_Z = 0$:

a) True vacuum bubble nucleation rate: $\Gamma = A\,\exp\{-S_E\}$

b) Euclidean action: $S_E = \frac{27\,\pi^2\,\tilde{S}^4}{2\,\Lambda_Z^{12}}$

c) Reduced action:
$\tilde{S} = \int_{a_Z=2\pi v_Z}^{a_Z=0} \sqrt{2(\Lambda_Z^4)[1-\cos\frac{a_Z}{v}]}\,da_Z = 8\,v_Z\,\Lambda_Z^2$

d) Bound:

$S_E \geq 5 \times 10^5\,(\frac{v_Z}{\Lambda_Z})^4 \geq 10^{65}$ for $v_Z \geq 1\,TeV$.

e) Transition time:

$\tau = \frac{3\,H}{4\,\pi\Gamma} \geq (10^{-106}\,s)\,\exp(10^{65})$. A very long time!

– The universe will enter an inflationary stage! Distant galaxies will disappear from our view, leaving us with just the Milky Way or our own cluster.

- Equation of state: $w = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{a_Z}^2 - V(a_Z)}{\frac{1}{2}\dot{a_Z}^2 + V(a_Z)} < 0$ for $\frac{1}{2}\dot{a_Z}^2 \ll V(a_Z)$.

  The present universe being trapped in a false vacuum, $\frac{1}{2}\dot{a_Z}^2 \sim 0 \Rightarrow w \approx -1$. It effectively mimics the ΛCDM scenario.

- Candidates for WIMP CDM:

  $\psi_{1,2}^{(Z)} = (3,1)$ under $SU(2)_Z \otimes SM$

  Mass $\sim$ O($100 - 200\, GeV$).

  Condition for $\psi^{(Z)}$ to be CDM candidates:

  $$\Omega_{\psi(Z)} = \frac{m_{\psi(Z)}\, n_{\psi(Z)}}{\rho_c\, h^2} \approx \left(\frac{3\times10^{-27}\, cm^3\, sec^{-1}}{\langle \sigma_{A,\psi(Z)}\, v\rangle}\right)$$

  with the annihilation cross section $\langle \sigma_{A,\psi(Z)} \rangle$ typically of the order of a weak cross section, i.e.$\langle \sigma_{A,\psi(Z)} \rangle 10^{-36}\, cm^2 \sim \frac{3\times10^{-9}}{GeV^2} \Rightarrow$ WIMP in order for $\Omega_{\psi(Z)} \sim O(1)$.

$\psi^{(Z)}$ with mass $\sim$ O(100−200 GeV) do just that since one expects $\langle\sigma_{A,\psi^{(Z)}}\rangle \sim \frac{\alpha_Z(T)^2}{m^2_{\psi^{(Z)}}}$ and $\alpha_Z(T)^2 \sim 6 \times 10^{-4}$ over a large range of energy down to $\sim 100\, GeV$.

- New mechanism for Leptogenesis via the decay of a "messenger" scalar field $\tilde{\varphi}_1^{(Z)} = (3, 1, 2, Y)$ under $SU(2)_Z \otimes SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$.

SM leptogenesis (hep-ph/0604063)

- $\tilde{\boldsymbol{\varphi}}^{(Z)}_{1,2}$ carrying no color quantum number, couple to SM leptons and $\psi^{(Z)}_{1,2}$ as

  $\mathcal{L}_{yuk} = \sum_{i,m}(g^{(i)}_{\tilde{\varphi}_1\,m}\,\bar{l}^m_L\,\tilde{\boldsymbol{\varphi}}^{(Z)}_1\,\psi^{(Z)}_{i,R} + g^{(i)}_{\tilde{\varphi}_2\,m}\,\bar{l}^m_L\,\tilde{\boldsymbol{\varphi}}^{(Z)}_2\,\psi^{(Z)}_{i,R})$ + H.c.

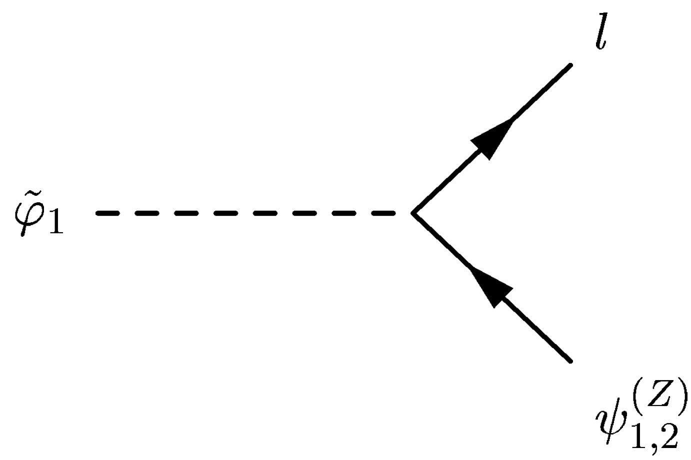
- Asymmetry in the decays (l: SM lepton)

  $\tilde{\varphi}^{(Z)}_1 \to \bar{\psi}^{(Z)}_{1,2} + l$, $\tilde{\varphi}^{(Z),*}_1 \to \psi^{(Z)}_{1,2} + \bar{l}$

  $\Rightarrow$ Net SM lepton number

  $\Rightarrow$ Net baryon number through EW sphaleron processes

- Asymmetry comes from interference between tree-level and one-loop decay: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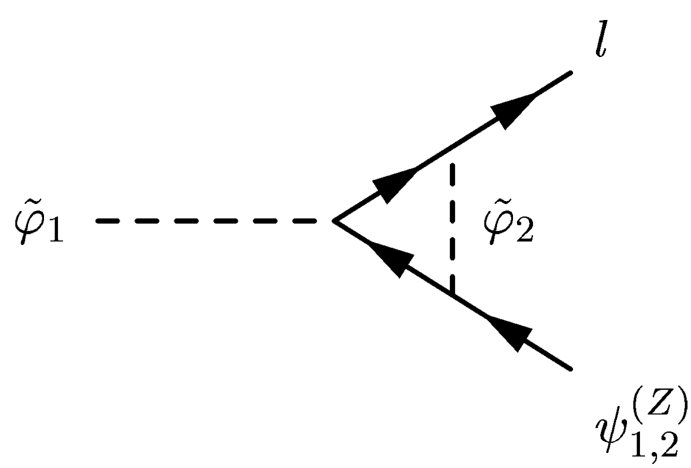
$\tilde{\varphi}_1$
$\psi_{1,2}^{(Z)}$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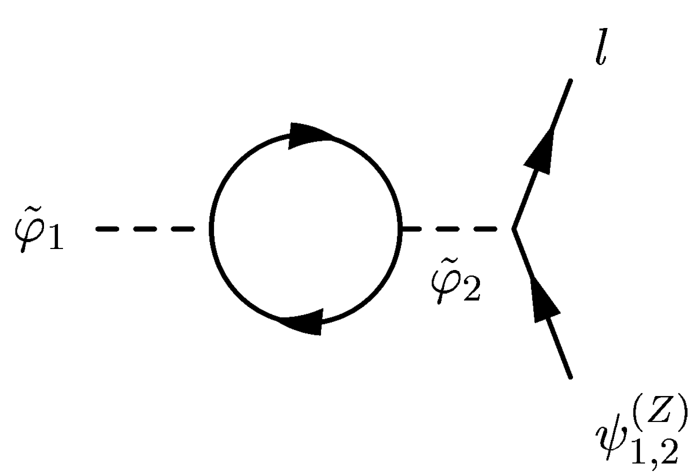
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$\tilde{\varphi}_1$
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$\psi_{1,2}^{(Z)}$

- For asymmetry $\neq 0$, we need two messenger fields: $\tilde{\boldsymbol{\varphi}}^{(Z)}_{1,2}$, with $m_{\tilde{\boldsymbol{\varphi}}^{(Z)}_2} \gg m_{\tilde{\boldsymbol{\varphi}}^{(Z)}_1}$.

- Asymmetry:

  $\epsilon^{\tilde{\varphi}_1} = \frac{\Gamma_{\tilde{\varphi}_1 l} - \Gamma_{\tilde{\varphi}^*_1 \bar{l}}}{\Gamma_{\tilde{\varphi}_1 l} + \Gamma_{\tilde{\varphi}^*_1 \bar{l}}}$

- SM lepton number asymmetry per unit entropy:

  $n_{LSM}/s \sim 2 \times 10^{-3}\, \epsilon_l^{\tilde{\varphi}_1}$

- Net baryon number per unit entropy:

  $n_B/s \sim -0.35\, n_{LSM}/s \sim -10^{-3}\, \epsilon_l^{\tilde{\varphi}_1}$

  $\Rightarrow \epsilon^{\tilde{\varphi}_1} \sim -10^{-7}$

- In this talk, specialize to the case where there is a permutation symmetry among the Yukawa couplings in the above interaction term. The asymmetry becomes

$$\epsilon_{tot} = 2\,[C_\mu\,(Im\{\delta\,I_\mu^{(1)}\} + Im\{\delta\,I_\mu^{(2)}\}) + C_\tau\,(Im\{\delta\,I_\tau^{(1)}\} + Im\{\delta\,I_\tau^{(2)}\})]/\sum_i |g_{\tilde{\varphi}_1\,i}|^2$$

$$C_\tau = |g_{\tilde{\varphi}_1\,\tau}|\,|g_{\tilde{\varphi}_1\,e}||g_{\tilde{\varphi}_2\,\tau}|\,|g_{\tilde{\varphi}_2\,e}|\,\sin(\kappa_{e\tau}) + |g_{\tilde{\varphi}_1\,\tau}|\,|g_{\tilde{\varphi}_1\,\mu}||g_{\tilde{\varphi}_2\,\tau}|\,|g_{\tilde{\varphi}_2\,\mu}|\,\sin(\kappa_{\mu\tau})$$

$$C_\mu = |g_{\tilde{\varphi}_1\,\mu}|\,|g_{\tilde{\varphi}_1\,e}||g_{\tilde{\varphi}_2\,\mu}|\,|g_{\tilde{\varphi}_2\,e}|\,\sin(\kappa_{e\mu}) - |g_{\tilde{\varphi}_1\,\mu}|\,|g_{\tilde{\varphi}_1\,\tau}||g_{\tilde{\varphi}_2\,\mu}|\,|g_{\tilde{\varphi}_2\,\tau}|\,\sin(\kappa_{\mu\tau})$$

$$Im\,\delta I_l^{(1,2)} = -\frac{1}{8\pi}(\frac{m_l}{m_{\tilde{\varphi}_1}})(\frac{m_{\psi_{1,2}^{(Z)}}}{m_{\tilde{\varphi}_1}})^3(1+\frac{1}{2}(\frac{m_{\psi_{1,2}^{(Z)}}}{m_{\tilde{\varphi}_1}})^2+..)$$

- Upper bound on $m_{\tilde{\varphi}_1}$:

  1) $|g_{\tilde{\varphi}_1\,e}| = |g_{\tilde{\varphi}_1\,\mu}| = |g_{\tilde{\varphi}_1\,\tau}|$

  $\Rightarrow \epsilon_{tot} \sim -10^{-7} < \frac{4}{3} Im\{\delta\, I_\tau\}$

  $\Rightarrow m_{\tilde{\varphi}_1} \leq 1\,TeV$

  2) $|g_{\tilde{\varphi}_1\,\tau}| \ll |g_{\tilde{\varphi}_1\,e}| = |g_{\tilde{\varphi}_1\,\mu}$ and $g_{\tilde{\varphi}_2\,\tau} \ll g_{\tilde{\varphi}_2\,e} = g_{\tilde{\varphi}_2\,\mu}$

  $\Rightarrow m_{\tilde{\varphi}_1} \leq 440\,GeV$

  3) $|g_{\tilde{\varphi}_1\,\mu}| \ll |g_{\tilde{\varphi}_1\,e}| = |g_{\tilde{\varphi}_1\,\tau}|$ and $g_{\tilde{\varphi}_2\,\mu} \ll g_{\tilde{\varphi}_2\,e} = g_{\tilde{\varphi}_2\,\tau}$

  $\Rightarrow m_{\tilde{\varphi}_1} \leq 1.1\,TeV$

  In many of these examples, $m_{\tilde{\varphi}_1} \leq 1\,TeV$.

  Chance for a detection of the “progenitor of the SM lepton asymmetry in this model!

Detection of the "lepton number progenitor" $\tilde{\varphi}_1^{(Z)}$

- Weak boson fusion:

  $W^+ W^- (\tilde{\varphi}_1^{(Z),0*} \tilde{\varphi}_1^{(Z),0} + \tilde{\varphi}_1^{(Z),+} \tilde{\varphi}_1^{(Z),-})$

  $Z\, Z\, (\tilde{\varphi}_1^{(Z),0*} \tilde{\varphi}_1^{(Z),0} + \tilde{\varphi}_1^{(Z),+} \tilde{\varphi}_1^{(Z),-})$

  Cross section $\sim 1 - 0.1 pb$ for $m_{\tilde{\varphi}_1} \sim 300 - 500\, GeV$.

- Observable decays $\tilde{\varphi}_1^{(Z),-} \rightarrow \bar{\psi}_{1,2}^{(Z)} + l_i^-$ (+ c.c.) with decay length $0.02\, cm < l_{\tilde{\varphi}_1} < 0.5\, cm$ for a 500 GeV messenger field, well within the silicon detector at ATLAS and CMS.

- The decay signatures have unsual geometry different from a SM Higgs with a mass $\sim 2\, m_{\tilde{\varphi}_1}$.

- The possible detection of the messenger field would provide (1) the key to leptogenesis in this model, and (2) an indirect signal of the CDM candidates $\psi_{1,2}^{(Z)}$.