GRK2044 Fall Workshop 2017

Breisach, 4-6 October 2017

Baryogenesis

Laura Covi

Institute for Theoretical Physics
Georg-August-University Göttingen

Outline

- Lecture 1:
  Introduction to CP violation & Baryogenesis
  Baryogenesis in the Standard Model
  Electroweak Baryogenesis BSM

- Lecture 2:
  Leptogenesis
  Affleck-Dine Baryogenesis
  Other mechanisms

Lecture 2: Outline

- Baryogenesis from out-of-equilibrium heavy particle decay
- Leptogenesis:
  Vanilla thermal leptogenesis
  Flavoured leptogenesis and thermal effects
- Affleck-Dine Baryogenesis
- Other mechanisms

Sakharov Conditions

Sakharov studied already in 1967 the necessary conditions for generating a baryon asymmetry from a symmetric state:

- B violation: trivial condition since otherwise B remains zero...
- C and CP violation: otherwise matter and antimatter would still be annihilated/created at the same rate
- Departure from thermal equilibrium: the maximal entropy state is for B = 0, or for conserved CPT, no B generated without time-arrow...

GUT baryogenesis

The first models of baryogenesis arose in the context of Grand Unified Theories, which naturally allow for baryon number violation (and also proton decay).
In particular the minimal GUT model is based on the gauge group SU(5), which contains SU(3)xSU(2)xU(1) and has the same rank.

SU(5) Gauge bosons: $\mathbf{24}$

$$\begin{pmatrix} g - \sqrt{\frac{2}{15}} B & \mathcal{X} \\ \mathcal{X} & W + \sqrt{\frac{3}{10}} B \end{pmatrix}$$

12 extra gauge bosons in the SM representation $(\bar{\mathbf{3}}, \mathbf{2}, \mathbf{5}/\mathbf{6})$

Fermions: $\bar{\mathbf{5}},\ \mathbf{10}$

$$\begin{pmatrix} d_r^c \\ d_b^c \\ d_g^c \\ e^- \\ \nu_e \end{pmatrix}$$

Proton Decay

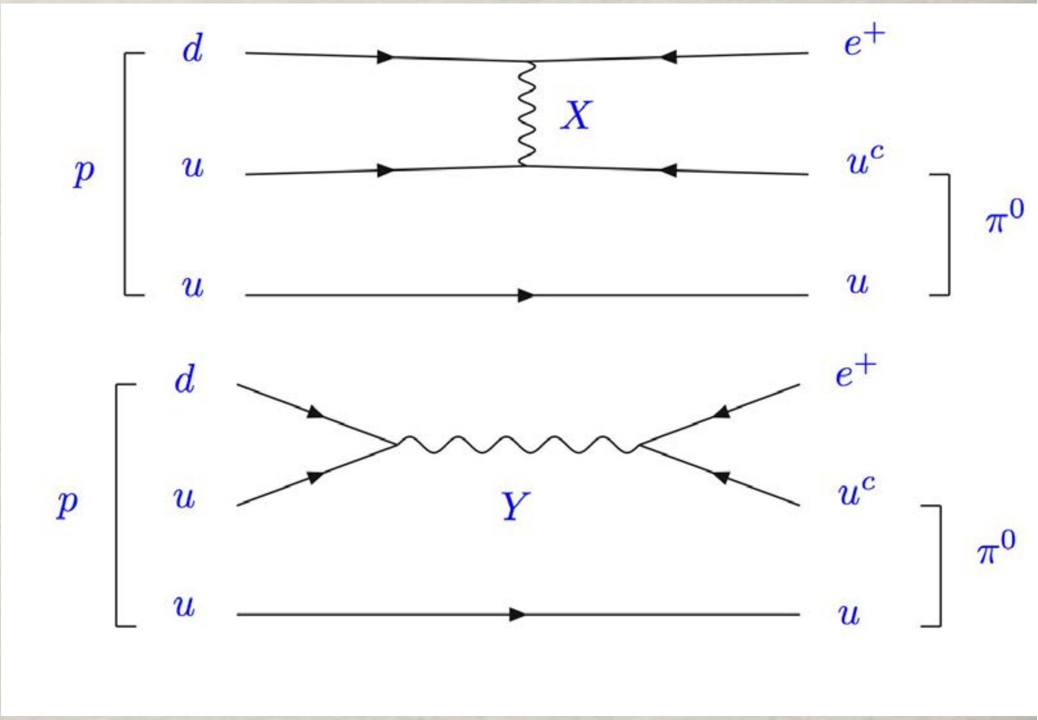
The new gauge bosons can mediate proton decay and give

$$p \to \pi^0 \ \ e^+$$

$$\tau_p \propto (G_p^2 m_p^5)^{-1}$$

$$G_p = \frac{g_{GUT}^2}{4\sqrt{2}M_X^2} \sim \frac{\alpha_{GUT}}{M_{GUT}^2}$$

$$\sim 10^{-34} GeV^{-2}$$



$$\tau_p \sim 10^{34} y$$

Very long lifetime !!!

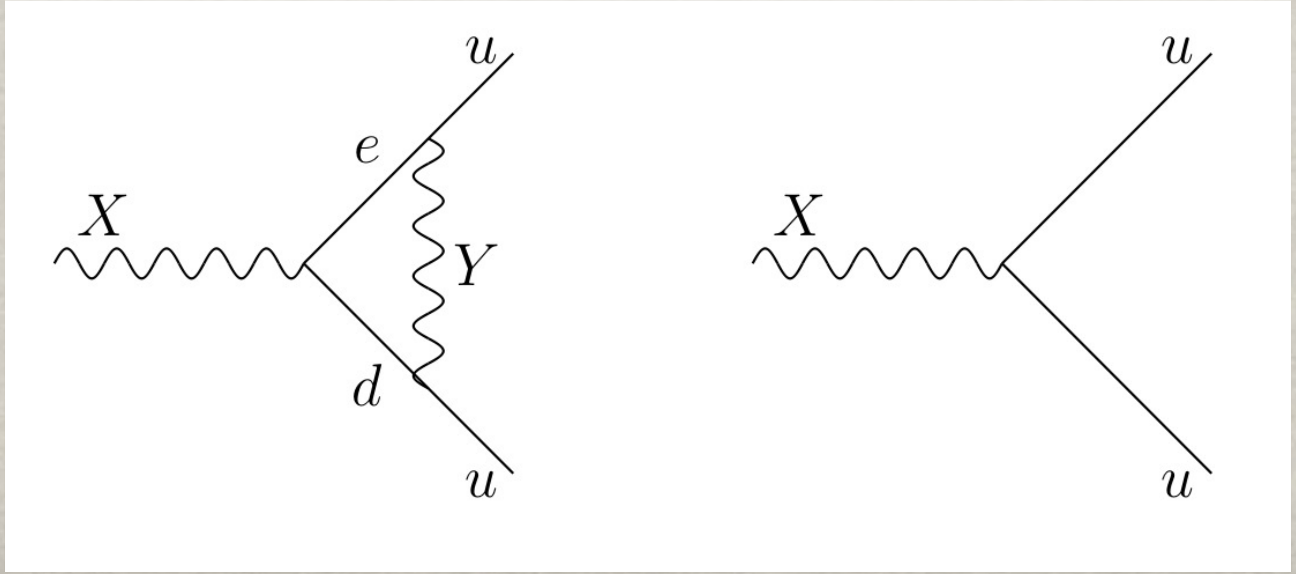
GUT BARYOGENESIS

Different decay channels: $\mathcal{X} = (X, Y)$

$$X \to u\,u,\;\; e^+\,\bar{d} \qquad\qquad Y \to d\,u,\;\; e^+\,\bar{u},\;\; \nu d$$

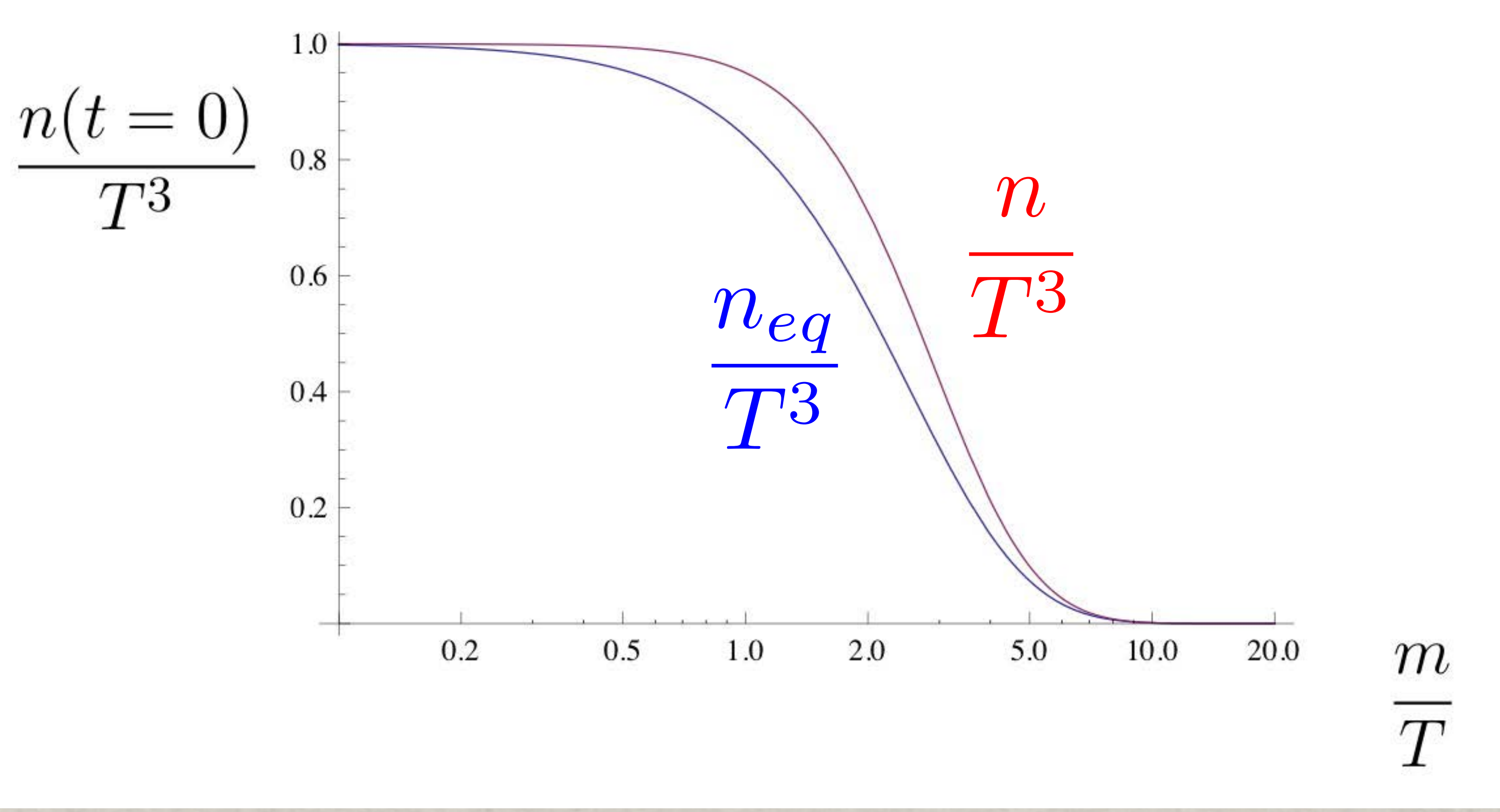
The decays violate baryon number !

C, CP violation arises from interference with the one-loop diagrams, as usual:



GUT BARYOGENESIS

Need still a deviation from thermal equilibrium: possible when the particle becomes non-relativistic and its density cannot follow the Boltzmann suppression



Just a small deviation is sufficient...

Sakharov Conditions II

For the Standard Model actually we have instead:

- B-L violation: B+L violation by the chiral anomaly

$$\partial_\mu J^\mu_{B+L} = 2n_f \frac{g^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- C and CP violation: present in the CKM matrix, but unfortunately quite small ! Possibly also additional phases needed...

- Departure from thermal equilibrium: phase-transition or particle out of equilibrium ?

Neutrino masses

The neutrinos are neutral and do not carry a conserved (local) charge, therefore in their case we can also write down a Majorana mass term in addition to the Dirac mass term.

e.g. dimension 5 Weinberg operator:

$$\frac{y}{M_P} \; H^* \bar{\ell}^c H \ell \quad \longrightarrow \quad \frac{y v_{EW}^2}{2 M_P} \; \bar{\nu}_L^c \nu_L$$

A Majorana mass matrix is symmetric and can be diagonalized by an orthogonal rotation, leaving more physical phases !

→ Pontecorvo-Maki-Nakagawa-Sakata mixing matrix with one Dirac phase δ and two Majorana phases α, β:

$$U_{PMNS} = P \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

with P = $\mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$ $\qquad s_{ij}, c_{ij} = \sin\theta_{ij}, \cos\theta_{ij}$

Neutrino masses & seesaw

[Minkowski 77, Gell-Mann, Ramond & Slanski 79, Yanagida 80]

Try to explain why the neutrino masses are so small: via the mixing with a very heavy state, the RH neutrino N !

$$W = Y_\nu LHN + \frac{1}{2} M_R NN$$

After the EW symmetry breaking we have a mixing between the LH neutrino and N and a Majorana mass term:

$$m_{N\nu} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

Eigenvalues:

$$m_\nu = -\frac{m_D^2}{M_R}, \; m_N = M_R$$

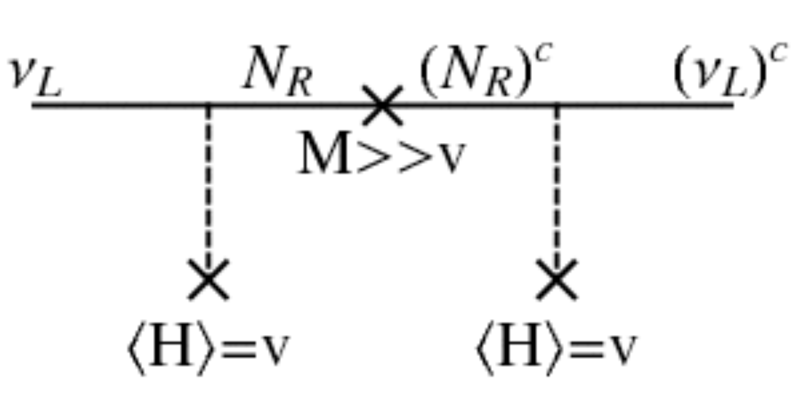
→ see-saw mechanism The larger M_R the smaller m_ν

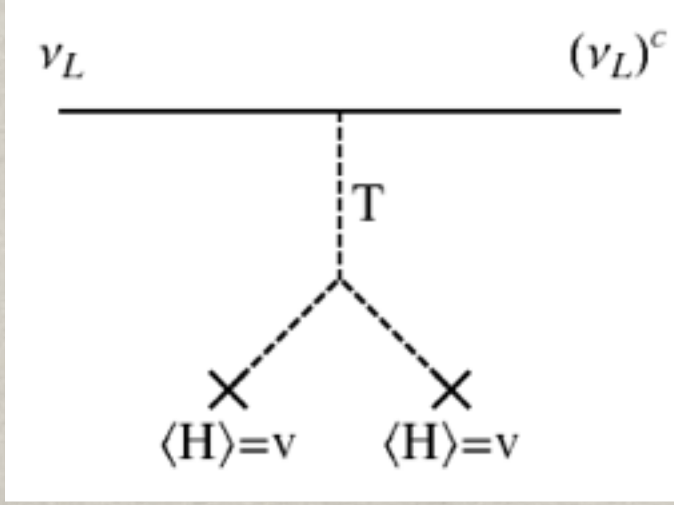
For $m_D \sim m_t$ need $M_R \sim 10^{15}\text{GeV}$

Neutrino masses & seesaw

Considering three generations, the light neutrino mass becomes a 3x3 Majorana mass matrix (type II see-saw):

$$m_\nu = -m_D^t \, M_R^{-1} m_D$$





Also other types of see-saw mechanism can be present, e.g. type I or even type III via an SU(2) triplet scalar or fermion. In all cases CP violation can arise !

Leptogenesis

Baryogenesis via Leptogenesis

[Fukugita & Yanagida '86]

Produce the baryon asymmetry from an initial lepton asymmetry reprocessed by the sphaleron transitions. Naturally possible in the case of see-saw mechanism for generating the neutrino masses.

$$W = Y_\nu LHN + \frac{1}{2} M_R NN \quad \longrightarrow \quad \text{see-saw}$$

Moreover the RH Majorana neutrino can generate a lepton asymmetry via decay if the rate also violates CP

$$N \to \ell\, H \qquad N \to \bar{\ell}\, H^\star$$

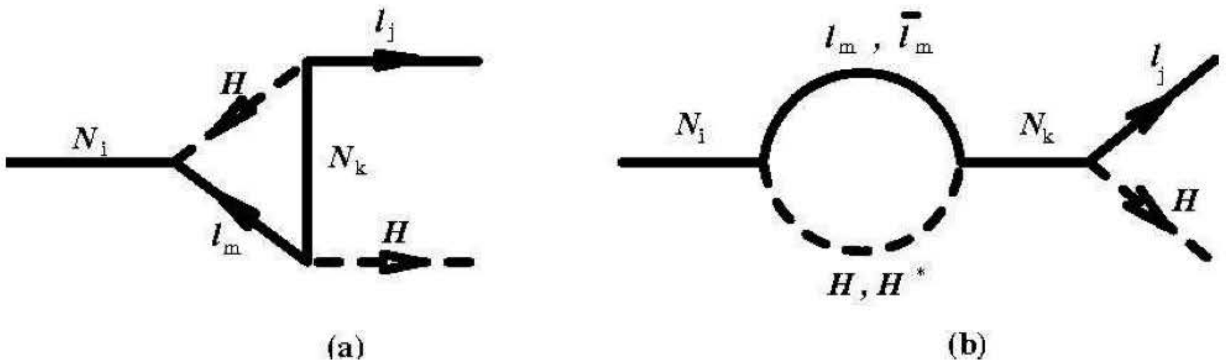
Both channel are possible due Majorana nature of N !

Thermal Leptogenesis

CP violation in N decay

We have CP in the decay of N if the couplings are complex.

CP violation always arises from an interference: tree + one-loop diagrams



We can define

$$\epsilon_i = \frac{\Gamma(N_i \to L) - \Gamma(N_i \to \bar{L})}{\Gamma(N_i \to L) + \Gamma(N_i \to \bar{L})} = -\frac{3}{16\pi} \sum_{i \neq j} \frac{M_i}{M_j} \frac{\Im[(Y_\nu^\dagger Y_\nu)^2_{ji}]}{(Y_\nu^\dagger Y_\nu)_{ii}} \text{ for } M_i \ll M_j$$

It is bounded !

$\rightarrow$relation to neutrino masses via Y_ν...

$$\epsilon \leq 10^{-6} \left(\frac{M_1}{10^{10}\ \mathrm{GeV}} \right) \frac{m_{atm}}{m_1 + m_3}$$

[Davidson & Ibarra 02]

Thermal Leptogenesis

The "back of the envelope" computation:

Out of equilibrium decay

To generate the lepton asymmetry we need also departure from thermal equilibrium: out of equilibrium decay of the lightest N. This happens if $\Gamma_1 \leq H$ at $T \sim M_1$.

$$\Gamma_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_1 \leq H = \sqrt{\frac{\pi^2 g_*}{90}} \frac{M_1^2}{M_P}$$

$\Rightarrow M_1 \geq \sqrt{\frac{90}{\pi^2 g_*}} \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_P$, i.e. the RH neutrino have to be sufficiently massive. Or one can refrase it as

$$\tilde{m}_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11} v^2}{M_1} \leq \sqrt{\frac{\pi^2 g_*}{90}} \frac{v^2}{M_P} \sim 10^{-3}\text{eV}$$

If this condition is satisfied, then it is trivial to see that every N gives an ϵ amount of lepton number and the final asymmetry is simply

$$\frac{n_L}{s} = \frac{n_{B-L}}{s} = \frac{135\zeta(3)g}{8\pi^4 g_S}\epsilon_1 \simeq 4\times 10^{-3}\epsilon_1 \quad \rightarrow \frac{n_B}{s} \sim -1.5\times 10^{-3}\epsilon_1$$

Otherwise one has to solve a couple of Boltzmann equations...

Thermal Leptogenesis

The solution of the coupled Boltzmann equations:

$$x = \frac{M_1}{T} \qquad Y_i = \frac{n_i}{s}$$

[Buchmüller, Di Bari & Plümacher '04]

$$\begin{cases} \dfrac{dY_{N_1}}{dx} = \underbrace{-(\Gamma + \sigma)}_{\text{Decay+Scattering}}(Y_{N_1} - Y_{N_1}^{eq}) \\ \dfrac{dY_{B-L}}{dx} = \underbrace{-\epsilon_1 \Gamma (Y_{N_1} - Y_{N_1}^{eq})}_{\text{Asymmetry in the Decay}} \underbrace{- W\, Y_{B-L}}_{\text{Wash-out term}} \end{cases}$$

Final result: $$Y_{B-L} = \epsilon_1 \underbrace{\kappa}_{\text{Efficiency factor}} Y_{N_1}(x \sim 1)$$

Thermal Leptogenesis

The solution of the coupled Boltzmann equations:

$$x = \frac{M_1}{T} \qquad Y_i = \frac{n_i}{s}$$

[Buchmüller, Di Bari & Plümacher '04]

$$\begin{cases} \dfrac{dY_{N_1}}{dx} = -(\Gamma + \sigma)(Y_{N_1} - Y_{N_1}^{eq}) \\ \dfrac{dY_{B-L}}{dx} = -\epsilon_1 \Gamma (Y_{N_1} - Y_{N_1}^{eq}) - W\, Y_{B-L} \end{cases}$$

Decay+Scattering

Asymmetry in the Decay

Wash-out term

Source of Lepton number

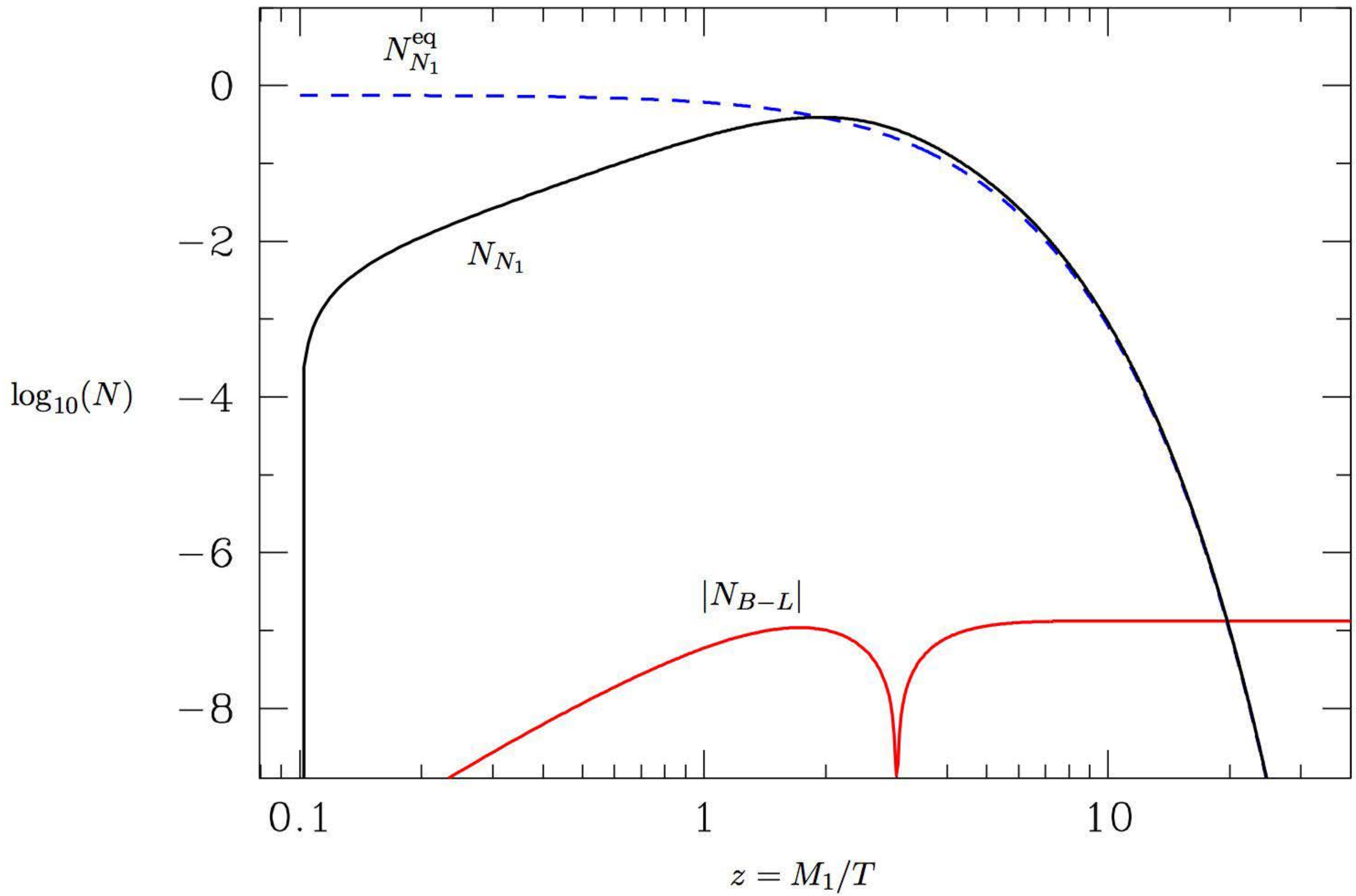
Final result: $$Y_{B-L} = \epsilon_1\, \kappa\, Y_{N_1}(x \sim 1)$$

Efficiency factor

Thermal Leptogenesis

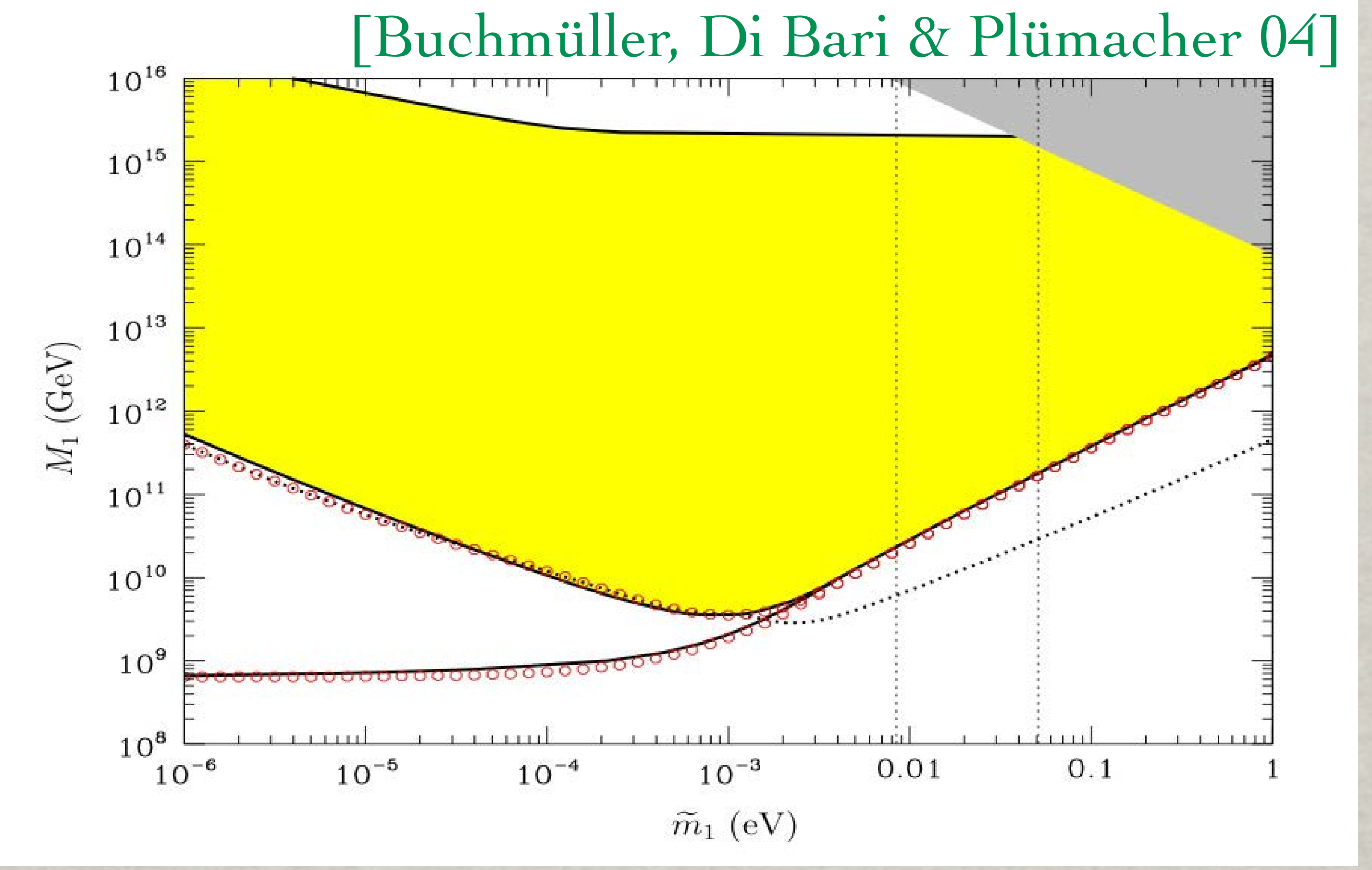
The solution of the coupled Boltzmann equations:

[Buchmüller, Di Bari & Plümacher '04]



Thermal Leptogenesis

M_1 must be large enough to generate the baryon asymmetry, for small M_1 the CP violation is just too small. Need large T_{RH} to produce the RH neutrino...



Ways out: enhanced CP violation due to degenerate N's, non-thermal leptogenesis, etc...

Low E vs high E CP ?

One important question is if the low energy leptonic CP violation observables are related to the CP violation in leptogenesis... Unfortunately not directly !

Simple parameter counting:

the 3x3 Majorana (low energy) mass matrix contains 9 real parameters, i.e. 3 masses, 3 mixings and 3 phases (1 Dirac & 2 Majorana phases), while the (high energy) Yukawa matrix & RH neutrino mass matrix amount instead to 18 real parameters.

In general the measurable low-energy Dirac phase in the neutrino sector is given by a complicated of the high energy parameters ! Nevertheless in specific models definite predictions are possible, e.g. 2 RH neutrino case or some flavoured leptogenesis cases...

Flavored Leptogenesis

[Abada et al, Nardi et al '06, De Simone et al '07....]

In the early universe the charged leptons have different thermal equilibration time due to the different Yukawa couplings, so the coherence of the light neutrino combination coupling to N_1 is not always ensured.

$T > 10^{12}\mathrm{GeV}$	Single flavour: all leptons NEQ	
$T \sim 5 \times 10^{11}\mathrm{GeV}$	Tau Yukawa is in equilibrium	2Flav
$T \sim 2 \times 10^{9}\mathrm{GeV}$	Muon Yukawa is in equilibrium	3Flav
$T \sim 4 \times 10^{4}\mathrm{GeV}$	Electron Yukawa is in equilibrium	

Depending on the epoch of leptogenesis, one may have to consider flavour effects !

Flavored Leptogenesis

[Abada et al, Nardi et al '06, De Simone et al '07....]

In presence of flavour, Yukawa scattering processes destroy coherence and project the lepton combination down to the flavour eigenstates. One can then define a CP asymmetry for every relevant flavour:

$$\epsilon_{1\alpha} = \frac{P_{1\alpha}\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1}$$

Similarly also wash-out processes can be different for the different flavours. So the possibility arises to store lepton number in the flavour with smaller wash-out rate !

More successful leptogenesis regions open up in general, but the prediction become flavour model-dependent.

Flavored Leptogenesis

[Abada et al, Nardi et al ‘06, De Simone et al ‘07....]

Different formalisms can be used to take into account flavour, depending on the regime.
Away from the transition between 1 - 2 flavours, one can use a flavoured Boltzmann equation, but this cannot take into account oscillations effects !

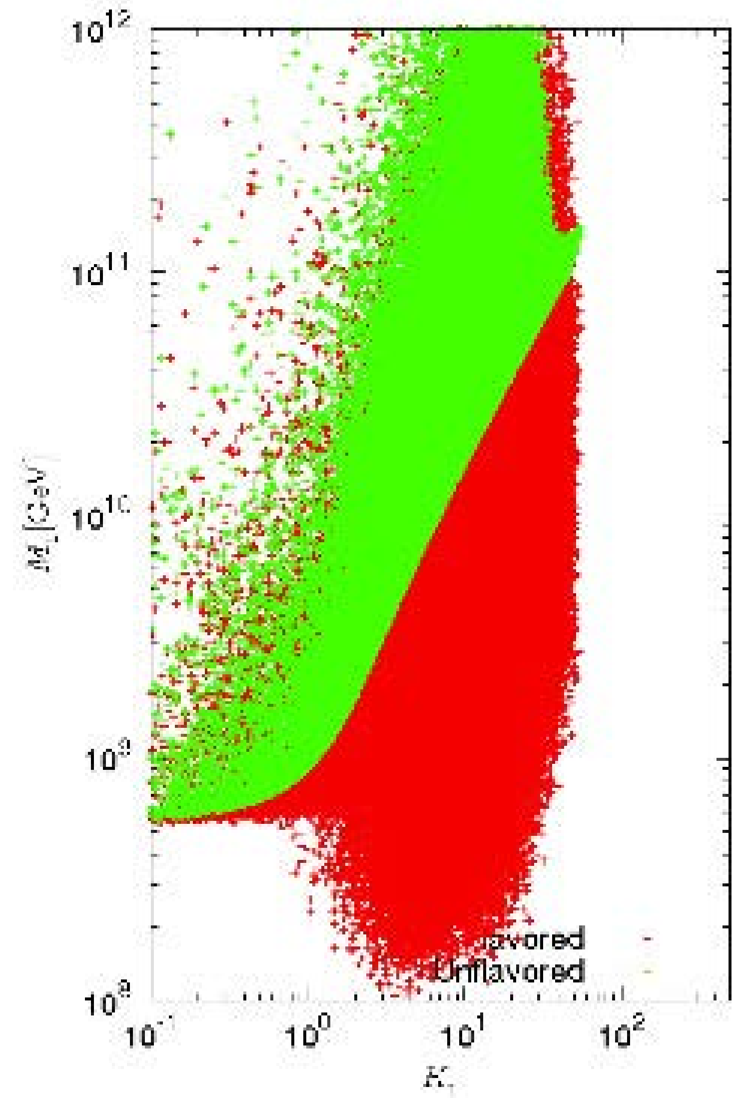
Another formalism is based on the full density matrix in flavour space and takes into account also the off-diagonal part, not included in the Boltzmann equations.

$$i\hbar\frac{\partial \rho}{\partial t} = [H, \rho]$$

Flavored Leptogenesis

One important issue is if flavour allows to extend the parameter region, where leptogenesis works.
Indeed, there are additional contributions to the Lepton asymmetry that cancel in the single flavour case !
Nevertheless not all is possible, thermal leptogenesis still works only at high temperature !

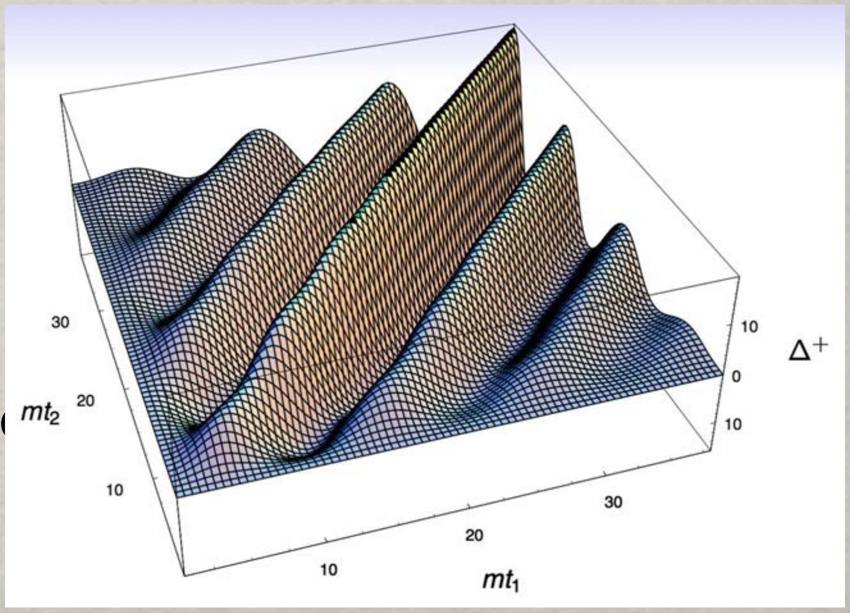
[Di Bari 1206.3168]



Quantum Leptogenesis

[Buchmüller et al, Garbrecht et al, Garny et al, Drewes et al, Pilaftsis et al...]

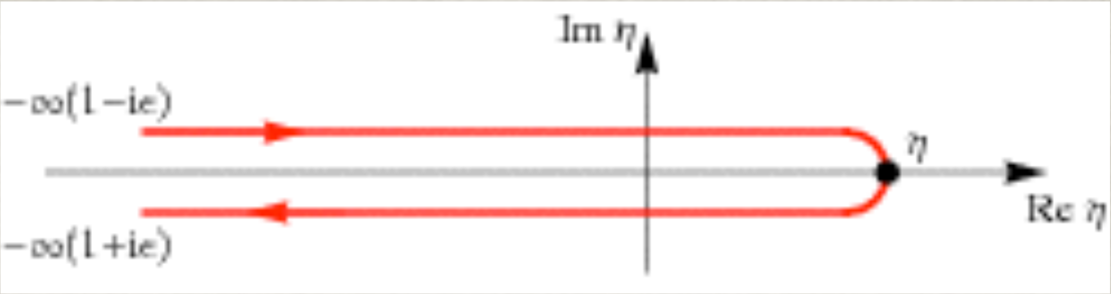
- Full quantum mechanical description of the process using Kadanov-Baym equations (2nd order) instead of the Boltzmann equations... No double counting and more effects (e.g. memory effects) arise !
- Different statistical/spectral propagators depending on two time variables and solutions include full particl



Quantum Leptogenesis

[Buchmüller et al, Garbrecht et al, Garny et al, Drewes et al....]

To describe the full non-equilibrium quantum evolution, exploit QFT in Closed-Time-Path formalism in order to compute in-in transition amplitudes



Propagators and Self-Energies become 2x2 Matrices

$$G = \begin{pmatrix} G^{++} & G^{+-} \\ G^{-+} & G^{--} \end{pmatrix} \qquad \Sigma = \begin{pmatrix} \Sigma^{++} & \Sigma^{+-} \\ \Sigma^{-+} & \Sigma^{--} \end{pmatrix}$$

Quantum Leptogenesis

[Buchmüller et al, Garbrecht et al, Garny et al, Drewes et al....]

To obtain the kinetic equations, start from the Schwinger-Dyson equation for the propagator:

$$G = G^0 + G^0 * \Sigma * G$$

From this one obtains the Kadanov-Baym equations for two combinations of the propagators: $G^{>,<} = G^{++} \mp G^{--}$

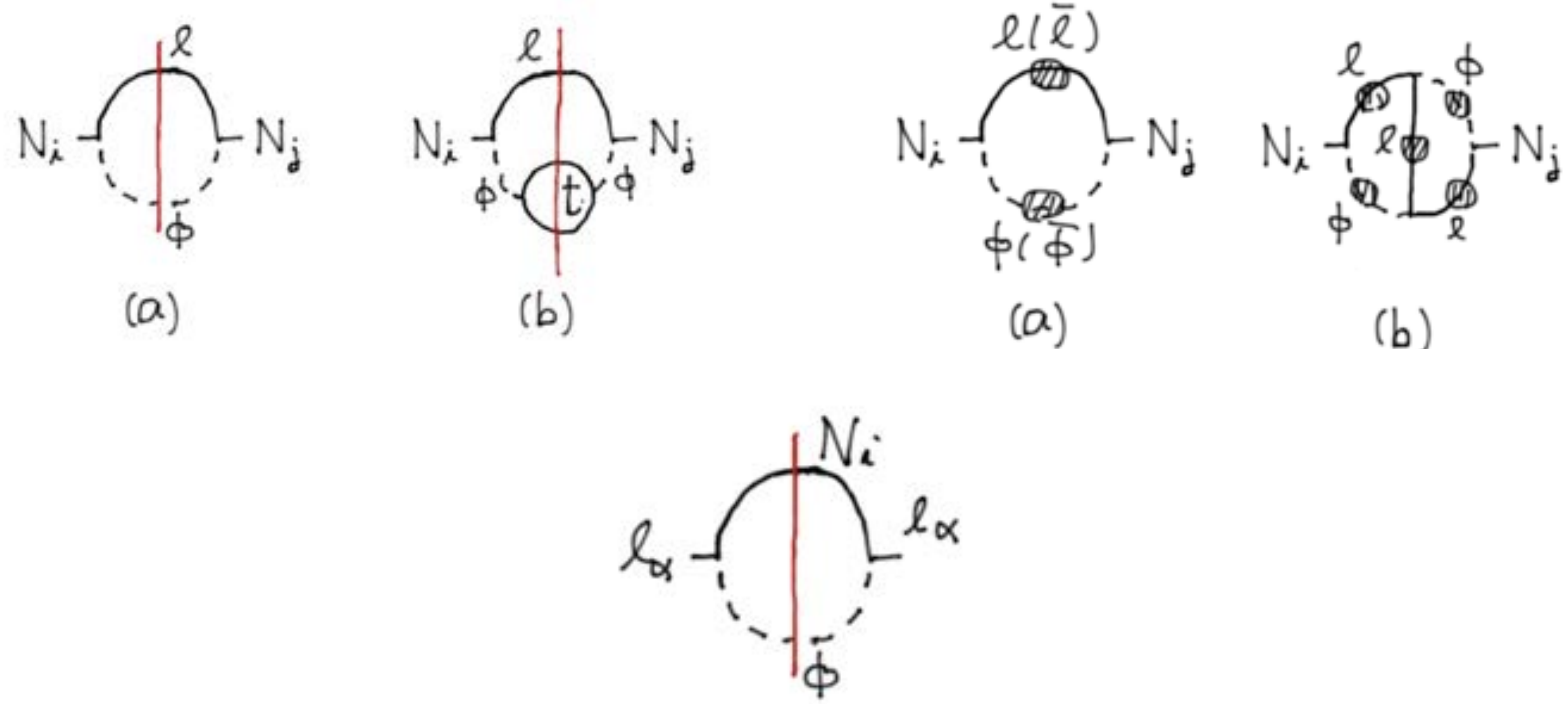
$$(i\gamma^\mu \partial_\mu - M_1)G^> = -\Sigma^> * G^>$$

$$(i\gamma^\mu \partial_\mu - M_1)G^< = \Sigma^> * G^< - \Sigma^< * G^>$$

This equations can then be expanded in gradient and perturbative series.

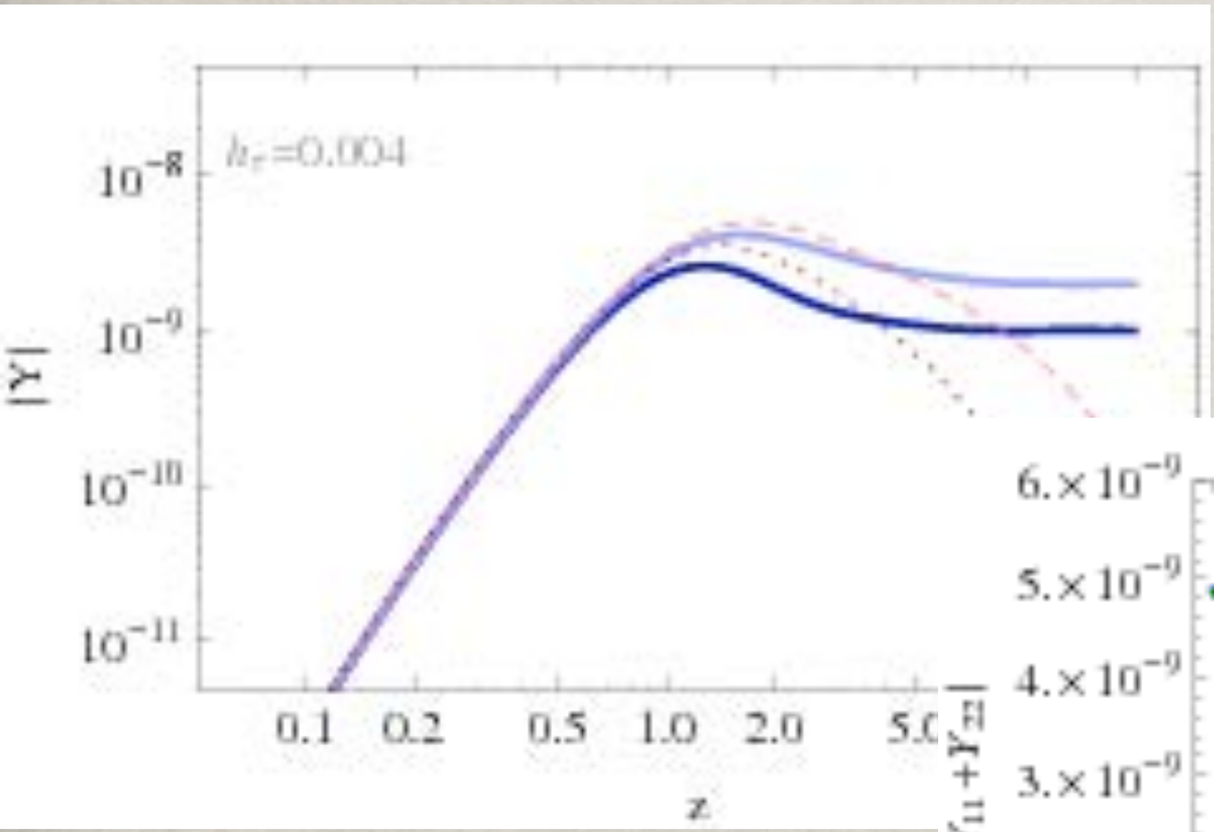
Quantum Leptogenesis

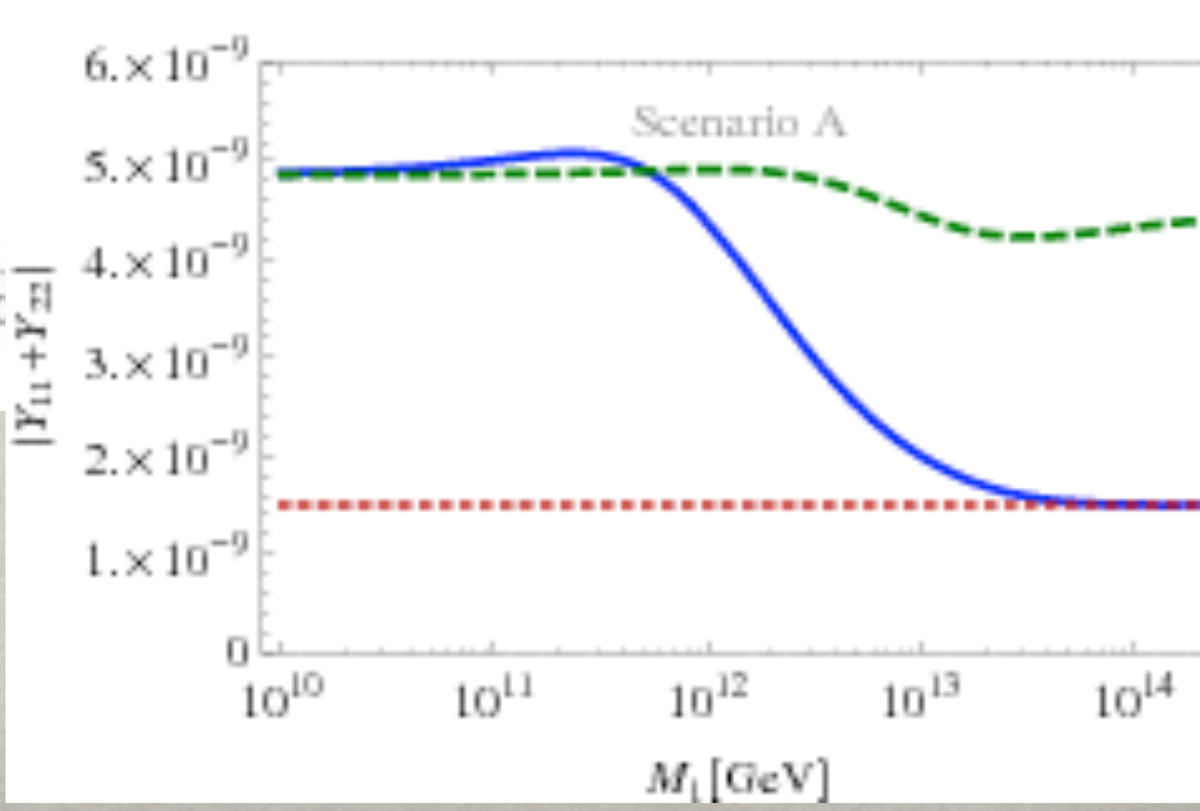
Where is the CP violation ??? In the self-energy !!!
Also includes scatterings and all possible processes automatically.



Quantum flavored Leptogenesis

[Beneke et al, 1007.4783]

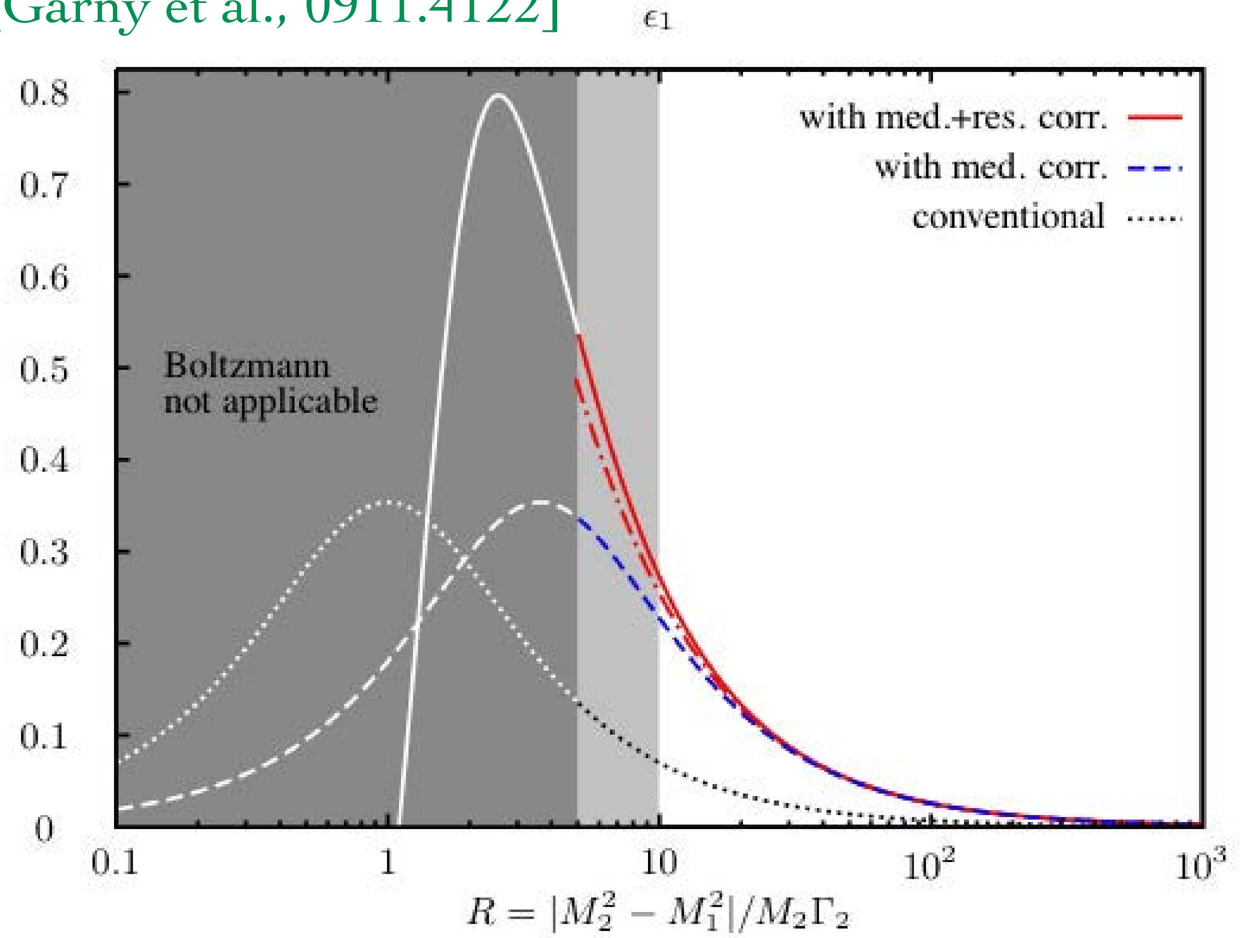




Quantum resonant Leptogenesis

[Garny et al.., Garbrecht et al...]

[Garny et al., 0911.4122]

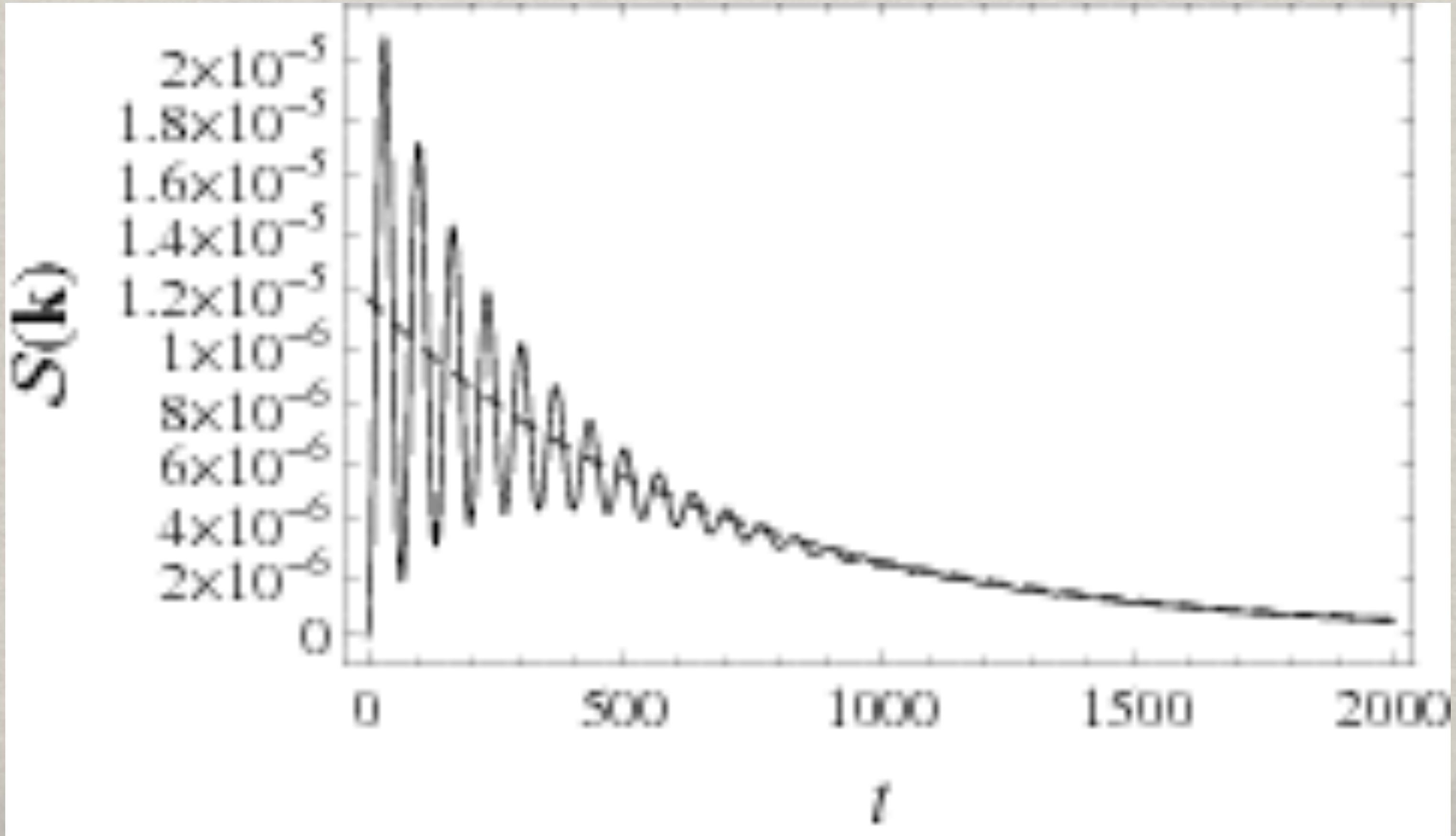


Resonant leptogenesis : the CP violation is enhanced if the mass difference is of the same order as the decay width.

Quantum resonant Leptogenesis

[Garny et al.., Garbrecht et al...]

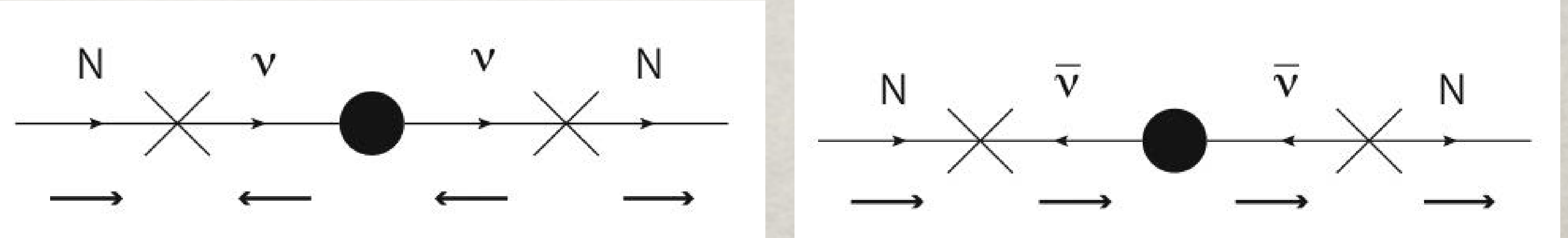
Resonant leptogenesis if two RH neutrinos are degenerate: oscillations !



Baryogenesis via neutrino oscillations

[E. Kh. Akhmedov, V. A. Rubakov & A. Yu. Smirnov 1998]

Leptogenesis can also proceed through classic heavy neutrino oscillations at a lower scale around 1-100 GeVs…



(a) Fermion number conserving process

(b) Fermion number violating process

nuSM Model with only 3 RH neutrinos: the two heavy ones around 1-10 GeV can generate the baryon asymmetry, while the third one with mass at keV is DM

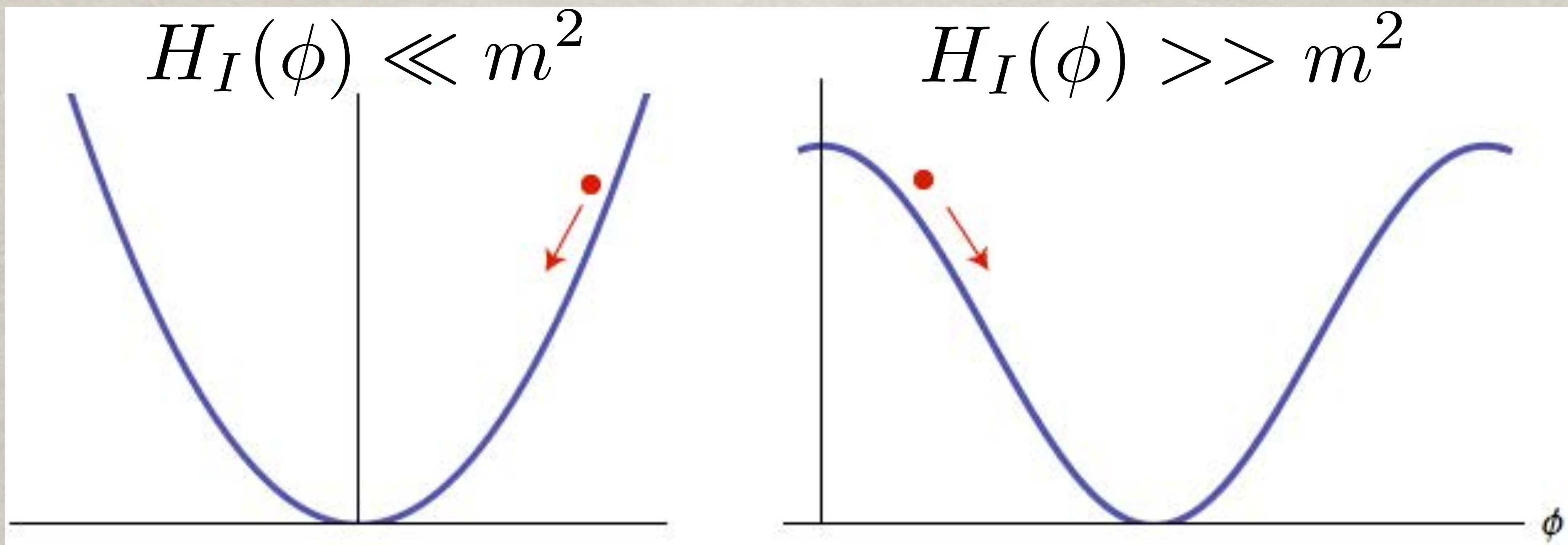
[T. Asaka & M. Shaposhnikov 2005]

Affleck-Dine baryogenesis

Light Field in cosmology

During inflation all scalar fields obtain a mass of order H_I which can be even negative and can effectively change the minimum of the scalar potential.

$$V(\chi) = \frac{1}{2} m^2 \phi^2 - c\, H_I^2(\phi) \chi^2 + \ldots$$



Light Field in cosmology

Moreover in cosmology a friction term appears in the equation of motions, due to the Universe's expansion:

$$\ddot{\chi} + 3H\dot{\chi} + (m^2 - 2c\,H^2)\chi + \ldots = 0$$

As long as $H > m$ the friction term dominates and the equation of motion is that of an overdamped harmonic oscillator. Therefore the field remains blocked at a constant value, even if it is not the minimum of the potential !

Only when H decreases sufficiently, can the force term overcome the friction and the classical field value goes towards the minimum.

Affleck-Dine Baryogenesis

[Affleck & Dine '85]

In the presence of Baryon-number carrying (complex) scalar fields, we see that the baryonic current is proportional to the time-derivative of the field phase:

$$n_b = j_b^0 = -i(\phi^* \partial^0 \phi - \phi\, \partial^0 \phi^*) = |\phi|^2\, \dot{\theta}$$

A non-trivial dynamic in the angular direction in a scalar condensate can generate a baryon asymmetry !

Need CP violating equation of motions, so that Real and Imaginary part of the scalar condensate evolve differently. In supersymmetric models such CP violating terms are naturally given by complex trilinear couplings A. "Out of equilibrium" condition provided by inflation...

Affleck-Dine Baryogenesis

[Affleck & Dine '85]

Consider for example a SUSY colored flat direction lifted only at the non-renormalizable level by

$$W = \frac{\lambda\, \chi^n}{n\, M_P^{n-3}}$$

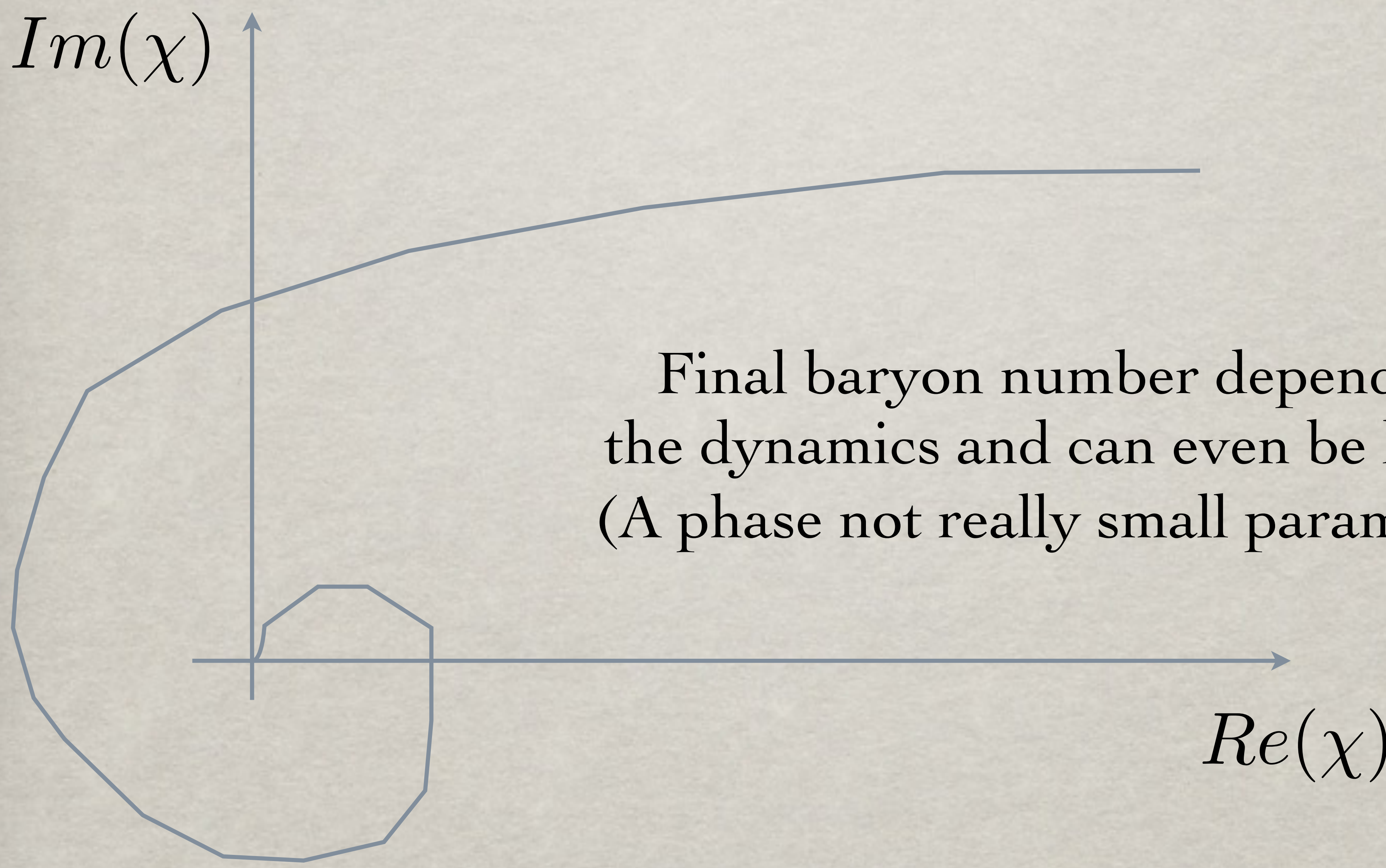
during inflation ($H_I >> m_{3/2}$) the v.e.v. sets at a large scale, while it relaxes later to the minimum at 0

$$V(\chi) = (m_{3/2} - cH_I^2)|\chi|^2 + \left[\lambda(aH_I + Am_{3/2})\frac{\chi^n}{nM_P^{n-3}} + h.c.\right] + |\lambda|^2 \frac{|\chi|^{2n-2}}{M_P^{2n-6}}$$

As long as $H_I >> m_{3/2}$ the mass term is negative and the scalar field acquires a non-zero vacuum expectation value away from the true minimum for $H_I \sim 0$.

Affleck-Dine Baryogenesis

[Affleck & Dine '85]



Final baryon number depends on the dynamics and can even be large... (A phase not really small parameter !)

But advantage: AD mechanism also effective at low T !

Affleck-Dine Baryogenesis

[Affleck & Dine '85]

During the relaxation we obtain a non-trivial baryon number if the trilinear coupling is complex since

$$\partial^0 n_b \sim -i(\chi^* \frac{\partial V}{\partial \chi} - h.c.) = -i|\chi|^2 m_{3/2} \left(\lambda A \frac{\chi^{n-2}}{M_P^{n-3}} - h.c. \right)$$

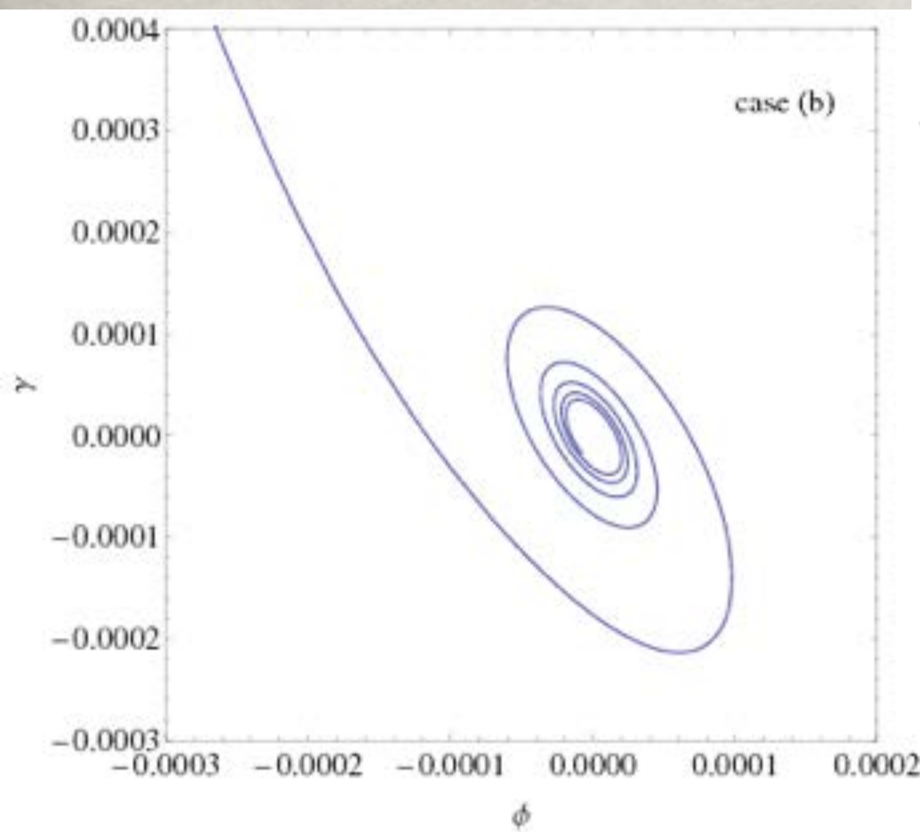
The main effect arises for large v.e.v of the field !
The value can oscillate with χ and it is transferred to fermions at the time the condensate decays:

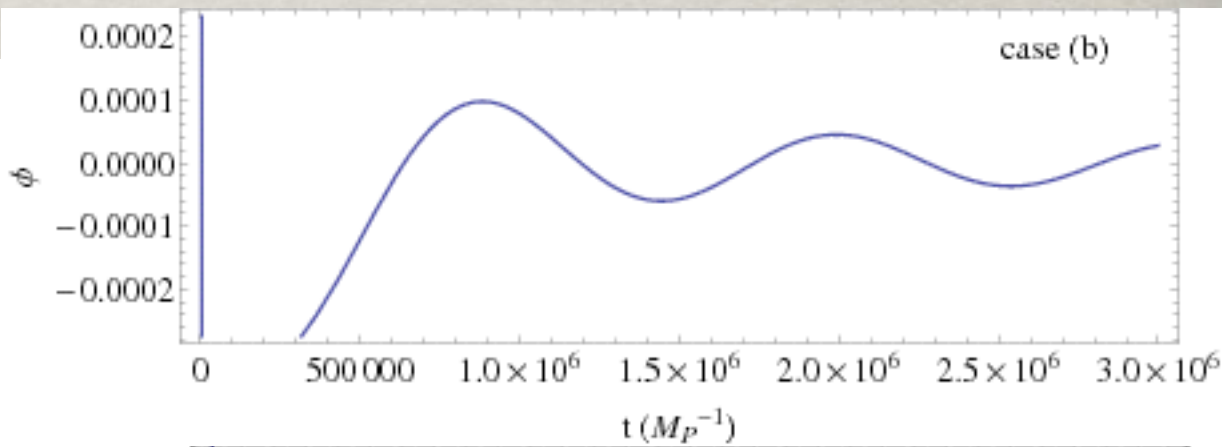
$$Y_B = \frac{n_b}{n_\chi} \frac{T_{RH} \rho_\chi}{m_{3/2} \rho_\phi} \sim 10^{-10} \left(\frac{T_{RH}}{10^6 \mathrm{GeV}} \right) \left(\frac{10^{-3}}{\lambda} \right)$$

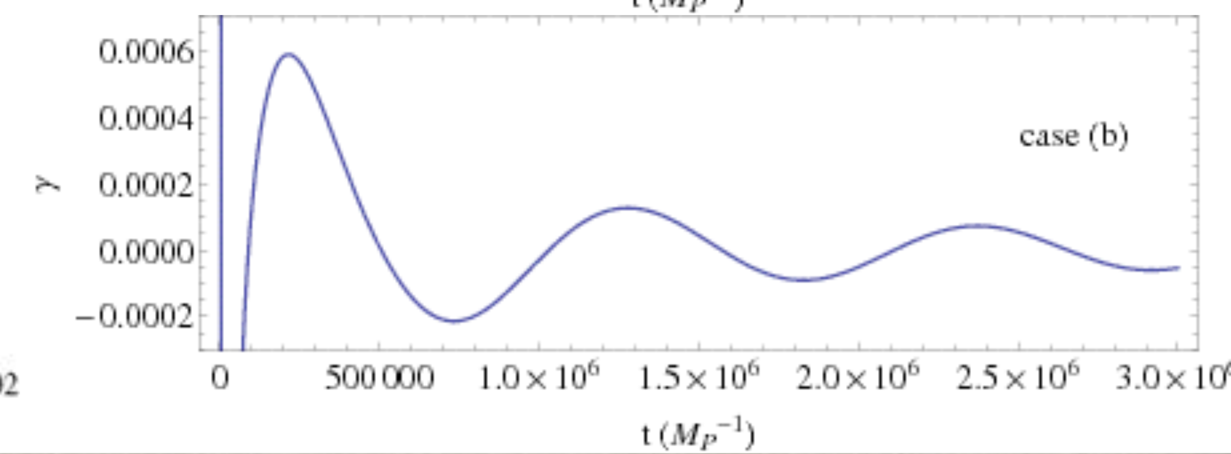
AD Baryogenesis in SUGRA

[Garcia & Olive '13]

Model of inflation with additional flat direction along LH direction producing AD leptogenesis. During inflation the flat direction follows the local minimum of the potential and at the end of inflation starts oscillating around the true vacuum



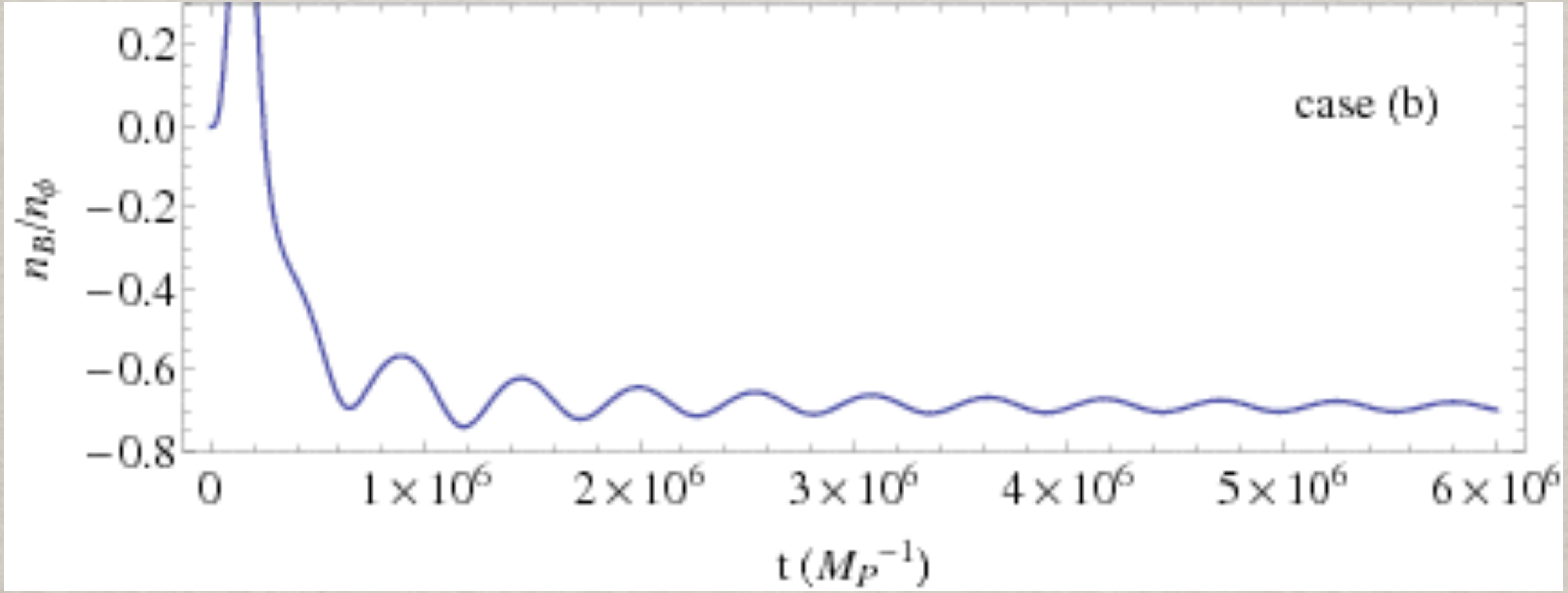




AD Baryogenesis in SUGRA

[Garcia & Olive '13]

While the LH flat direction oscillates, the lepton number is produced and then oscillates around a constant value.

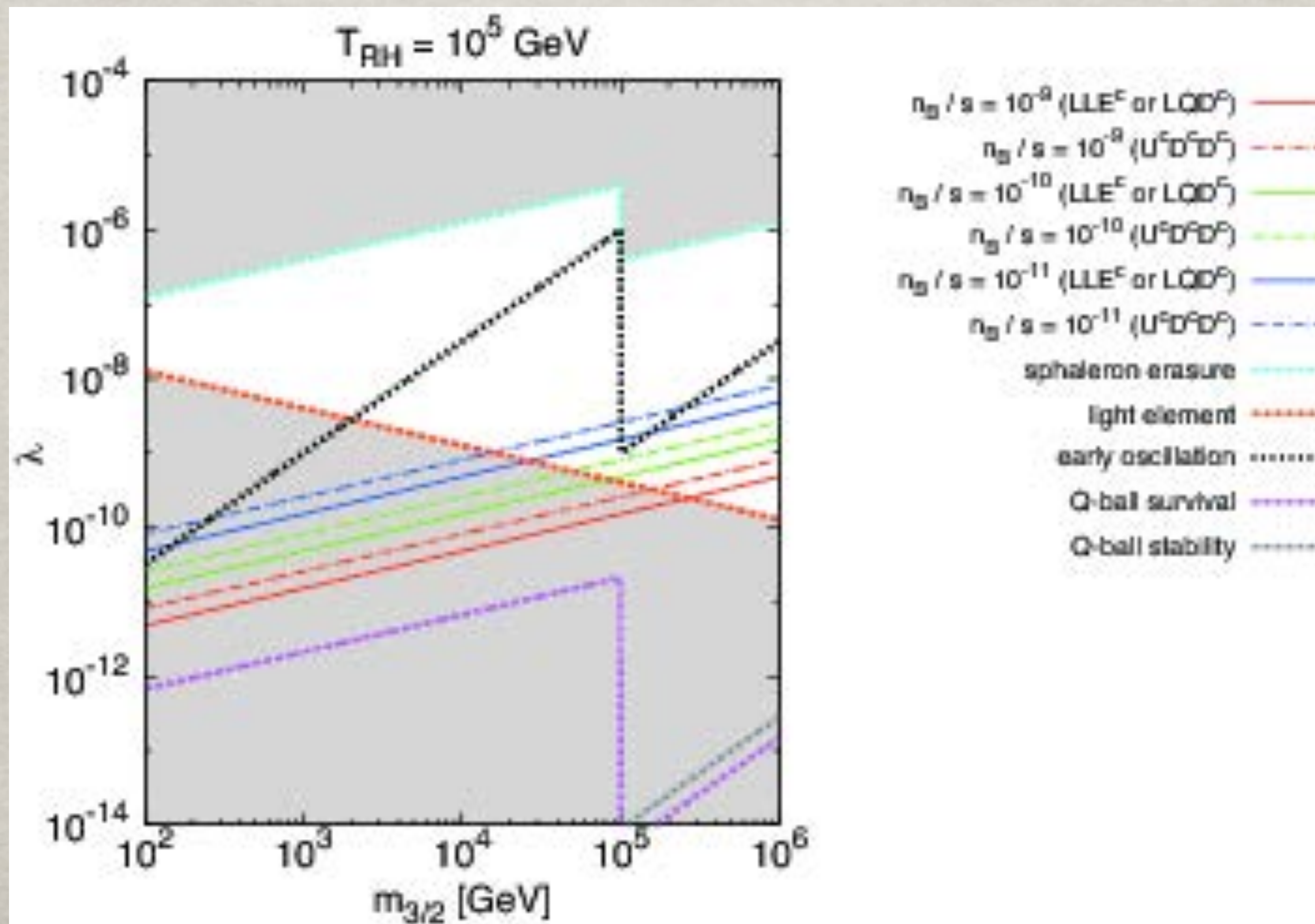


In this case need sufficiently high T_RH to allow for sphaleron processes to reprocess L into B

AD Baryogenesis with RPV

[Higaki et al ’14]

Also Baryon carrying flat-directions like UDD or LQD can be exploited. In that case the complex phase can also come from small RPV couplings, but makes the generation more difficult.

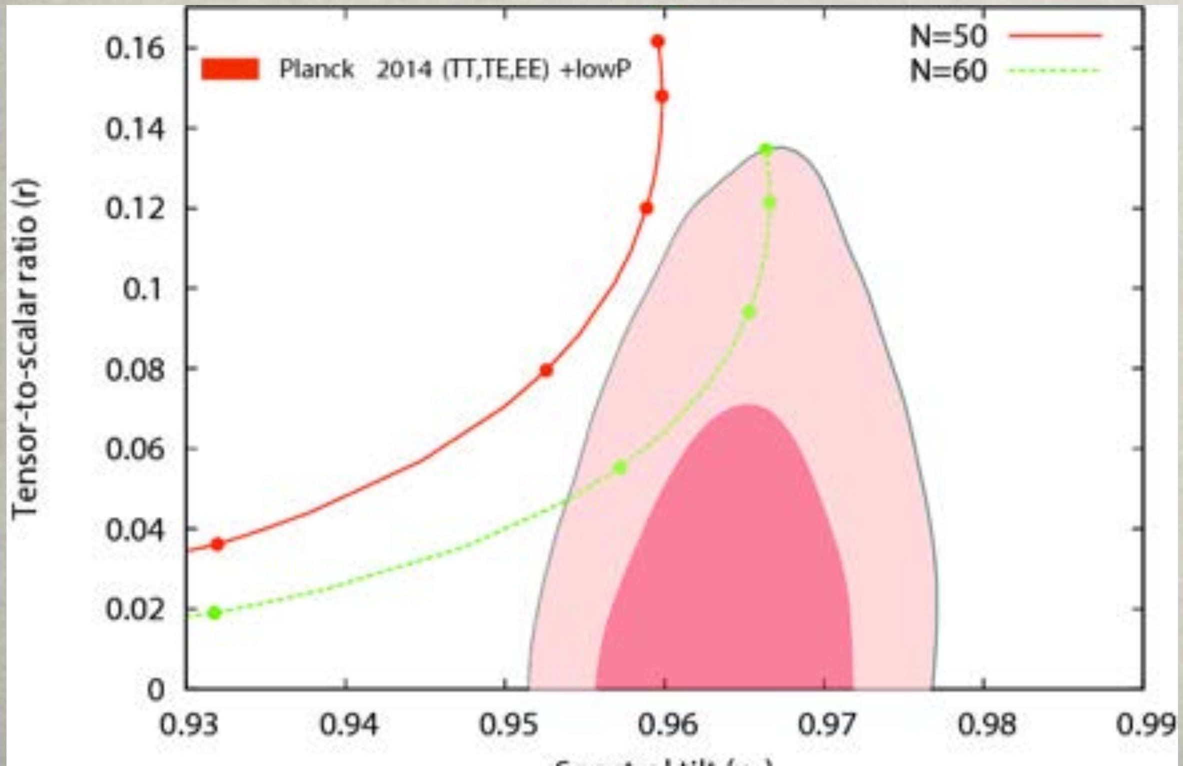


AD sneutrino inflation

[Evans, Gherghetta & Peloso '15]

Inflation along a trajectory in 2 sneutrinos direction. Solving the eom for the heavier field, one has the single field potential

$$V = \frac{1}{2} m^2 \phi^2 \left[1 - a\,\phi^{4/3} - b\,\phi^2\right]$$



Flatter than a simple mass term and therefore still acceptable compared to Planck data for large N

AD sneutrino inflation

[Evans, Ghergghetta & Peloso '15]

Leptogenesis then proceeds if one adds a small imaginary part to the inflaton mass, shifting the trajectory to become non-trivial in the complex plane and generating an L number. At the end of inflation the 4 real scalar fields oscillate around the minimum in a non-trivial way, giving rise to an oscillating asymmetry:

$$n_L = C_{nl}\left[(\lambda_n + \lambda_l)\sin\left((\lambda_n - \lambda_l)\tau + \delta'\right) + \ldots\right]$$

At the time of decay of the condensate, this gives

$$n_L \simeq -\xi_0 \frac{\mu_I \mu_{3/2}\, t\, m^2\, M_p^2}{\mu_R^{2/3} a^3} + \mathcal{O}\left(\mu_I \mu_{3/2}^2, \mu_I^2 \mu_{3/2}\right) ,$$

$$\xi_0 \equiv \frac{\phi_{1I}(t_0)}{M_p} \frac{\phi_{2I}(t_0)}{\mu_R^{1/3} M_p}\left(1 + \frac{\dot{\phi}_I^2(t_0)}{3m^2 \phi_{1I}^2(t_0)}\right) + \mathcal{O}\left(\mu_R^{2/3}\right)$$

$$Y_B \equiv \frac{n_B}{s} \simeq \frac{\mu_I\, \mu_{3/2}}{27\, \mu_R^{2/3}} \sqrt{\frac{M_p}{\Gamma}} ,$$

Other mechanisms

The Dark Matter-baryogenesis connection

Asymmetric Dark Matter

[Griest & Seckel '87, Kaplan, Luty &Zurek 90, ...]

Assume instead that there is an asymmetry stored in DM as in baryons: DM asymmetry generated in the same way as the baryon asymmetry..
It may also be generated together with the baryon asymmetry and then it is natural to expect the SAME asymmetry in both sectors.

$$\Psi \to B + X$$

$$n_{DM} \sim n_b \to \Omega_{DM} \sim 5\,\Omega_b$$

$$\text{for}\; m_{DM} \sim 5\,m_p = 5\,\text{GeV}$$

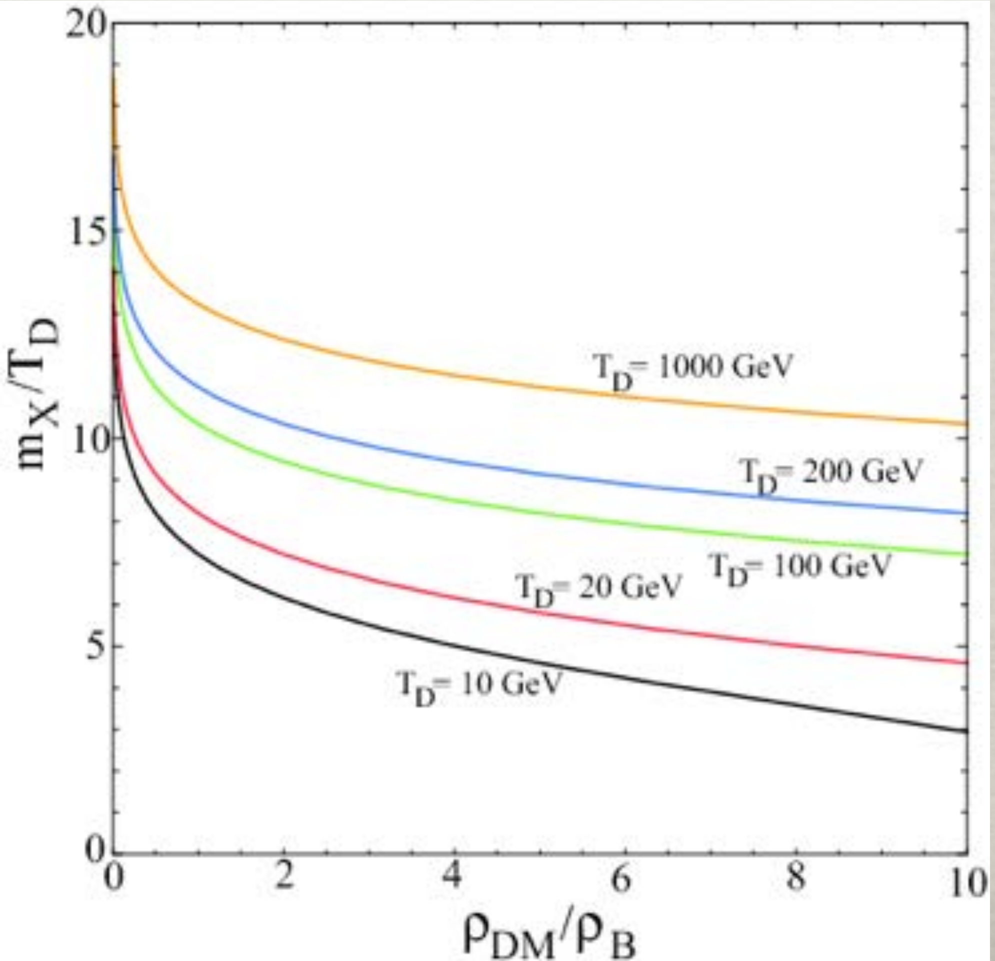
The puzzle of similar densities can be given by similar masses !

Asymmetric Dark Matter

[Griest & Seckel '87, Kaplan, Luty &Zurek 90, ...]

The simple picture $m_{DM} = 5\, m_p$ can be extended by taking into account the Boltzmann suppression factor at the time of creation of the asymmetry:

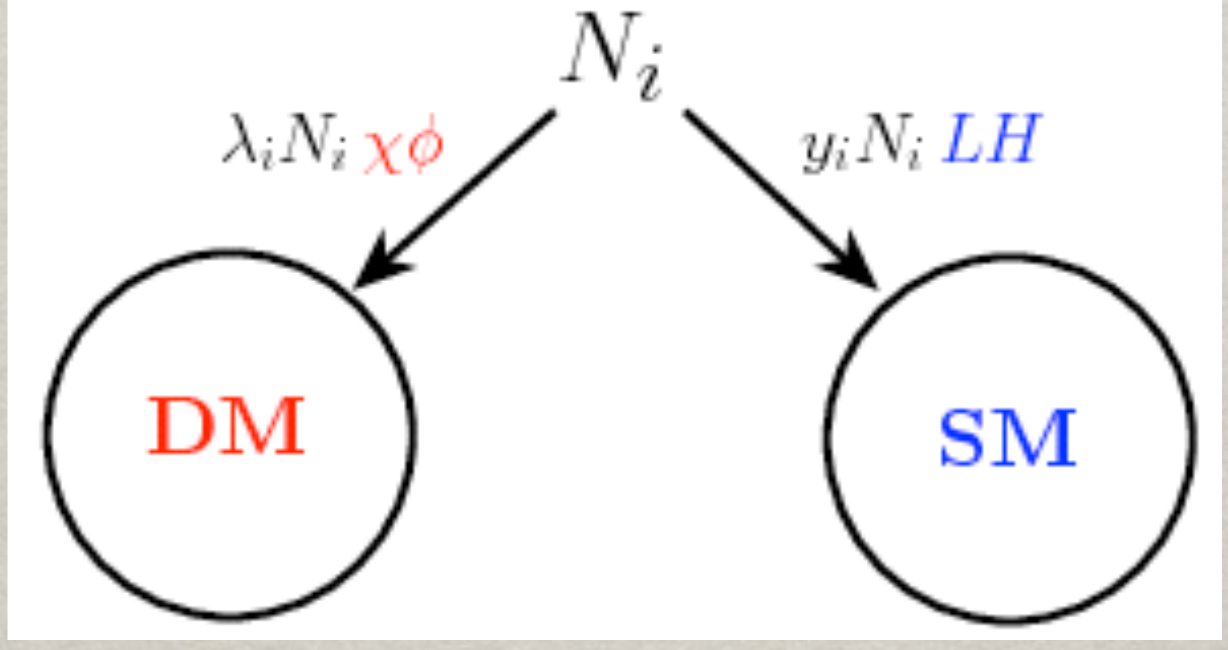
DM Mass/
T_Decoupling



Asymmetric Dark Matter

[Griest & Seckel '87, Kaplan, Luty &Zurek 90, ...]

Simple mechanism to generate such case:
out-of-equilibrium decay of a particle producing both B-L and DM, e.g. even decay of a RH neutrino

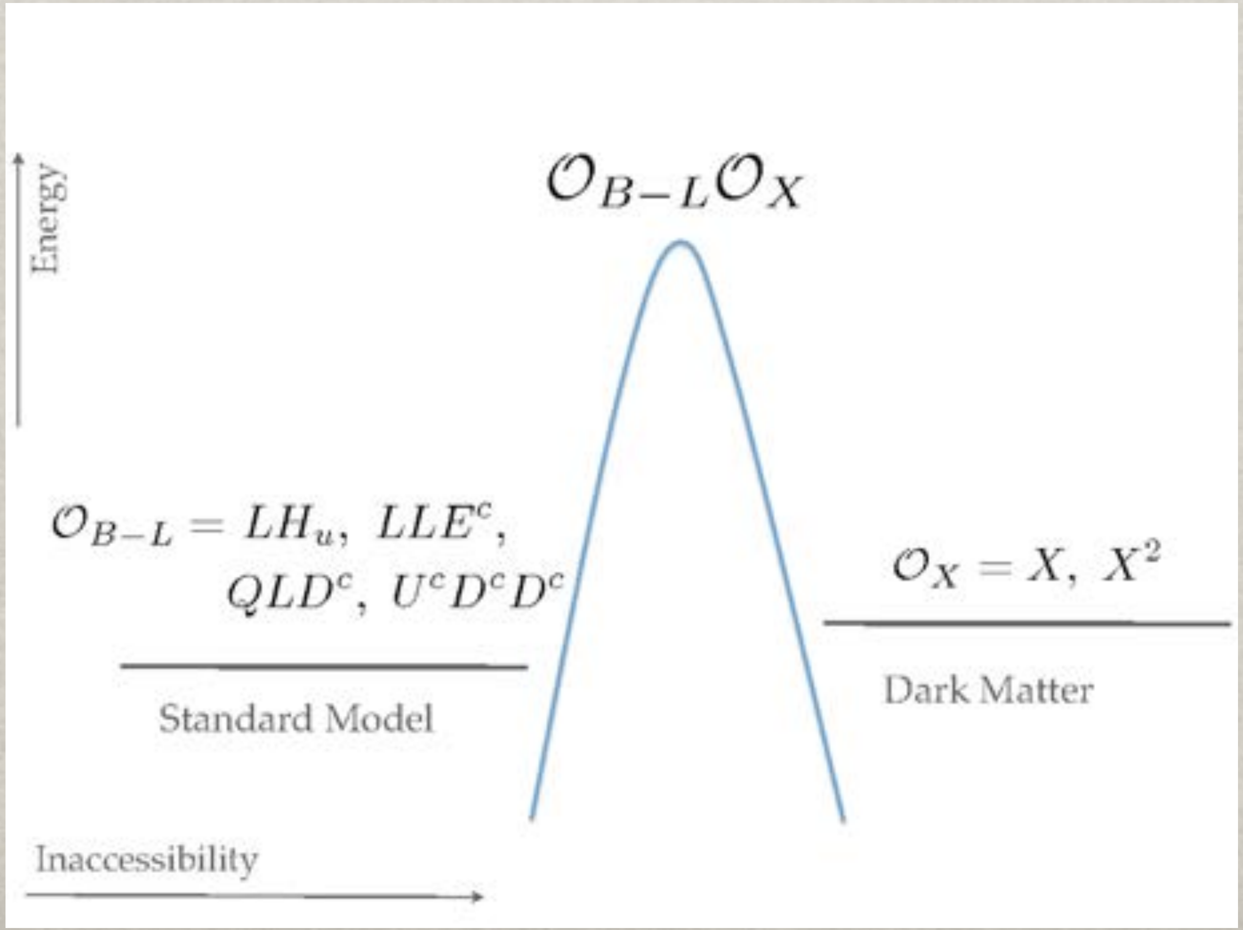


Need similar CP violation in both sectors !

Asymmetric Dark Matter

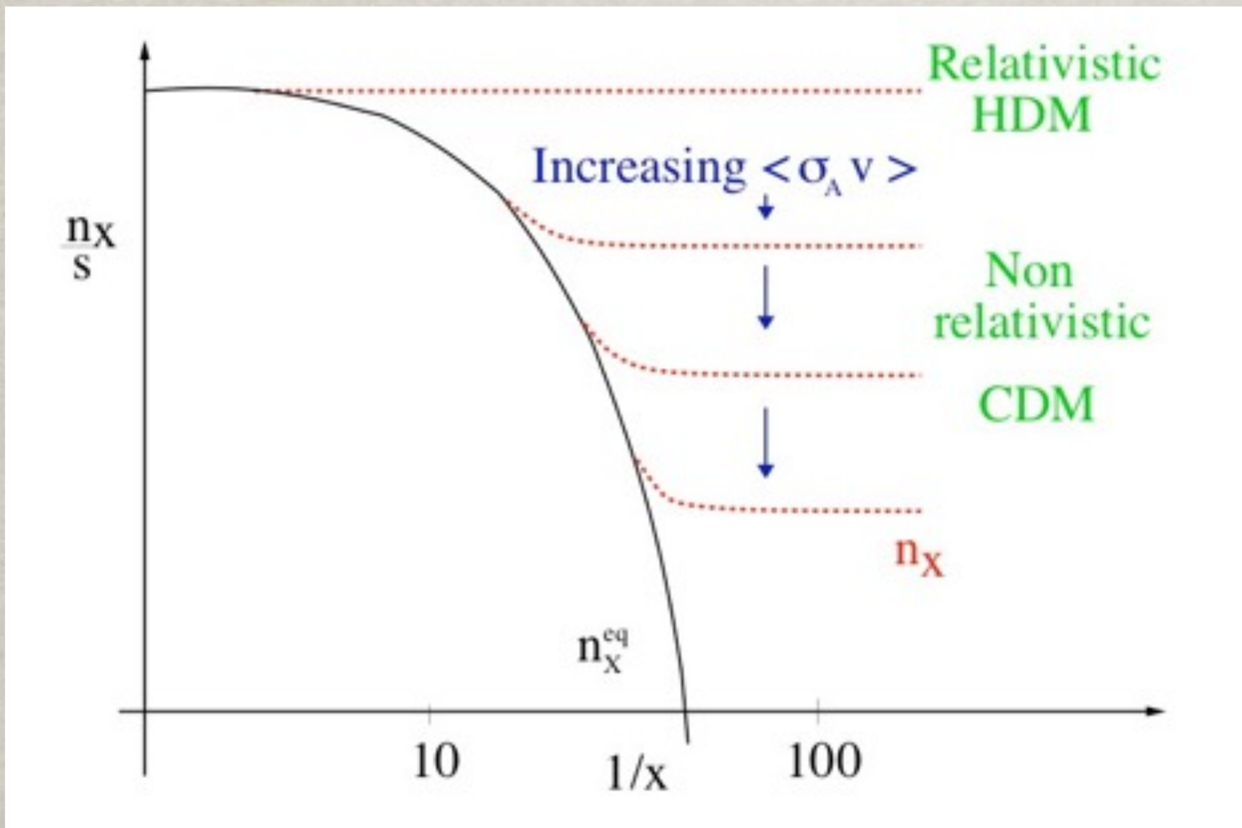
[Griest & Seckel '87, Kaplan, Luty &Zurek 90, ...]

Otherwise B-L can be produced and then reprocessed into DM/B/L by sphaleron processes. All other coupling exchanging DM/B frozen out !



Asymmetric Dark Matter

DM must annihilate sufficiently strongly to erase the symmetric DM component, so it may also interact more strongly than a WIMP with normal matter...



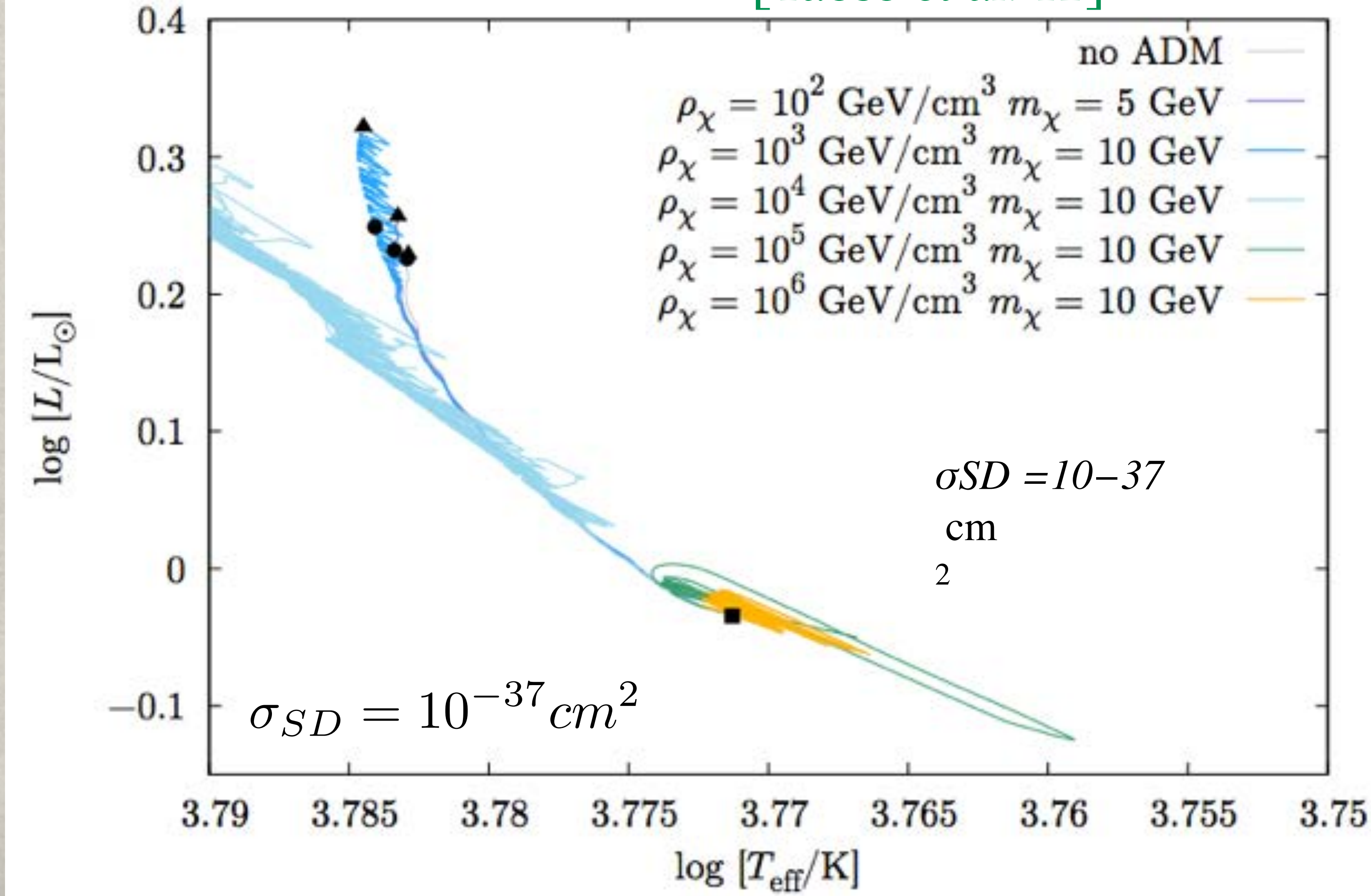
Strong coupling...
...like baryons !

It may accumulate in stars and change the star evolution...

Asymmetric Dark Matter

Possible signal in the star evolution if the DM can accumulate in the core of the star...

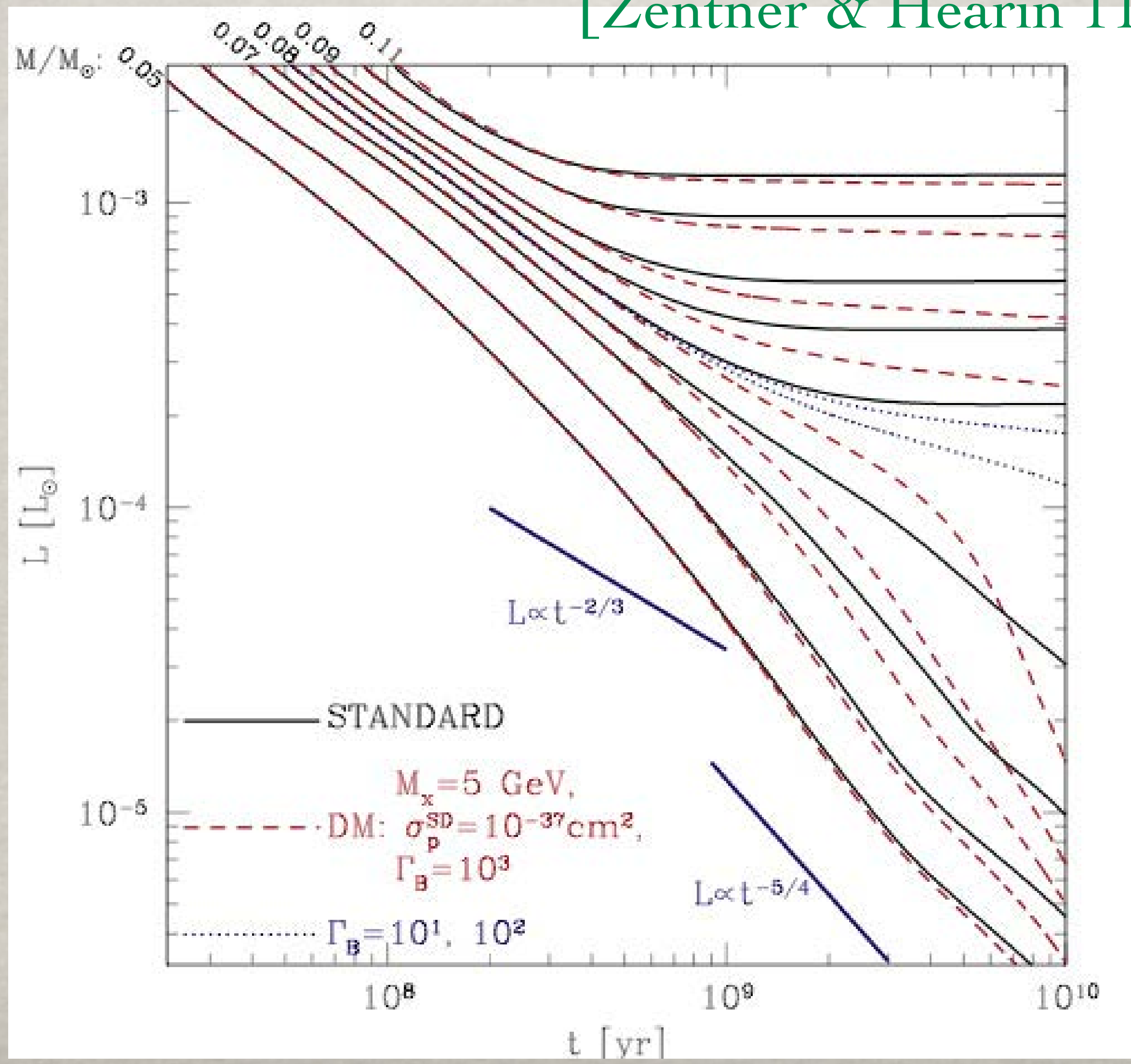
[Taoso et al. 12]



Asymmetric Dark Matter

Possible signal in the star evolution if the DM can accumulate in the core of the star...: Brown dwarves

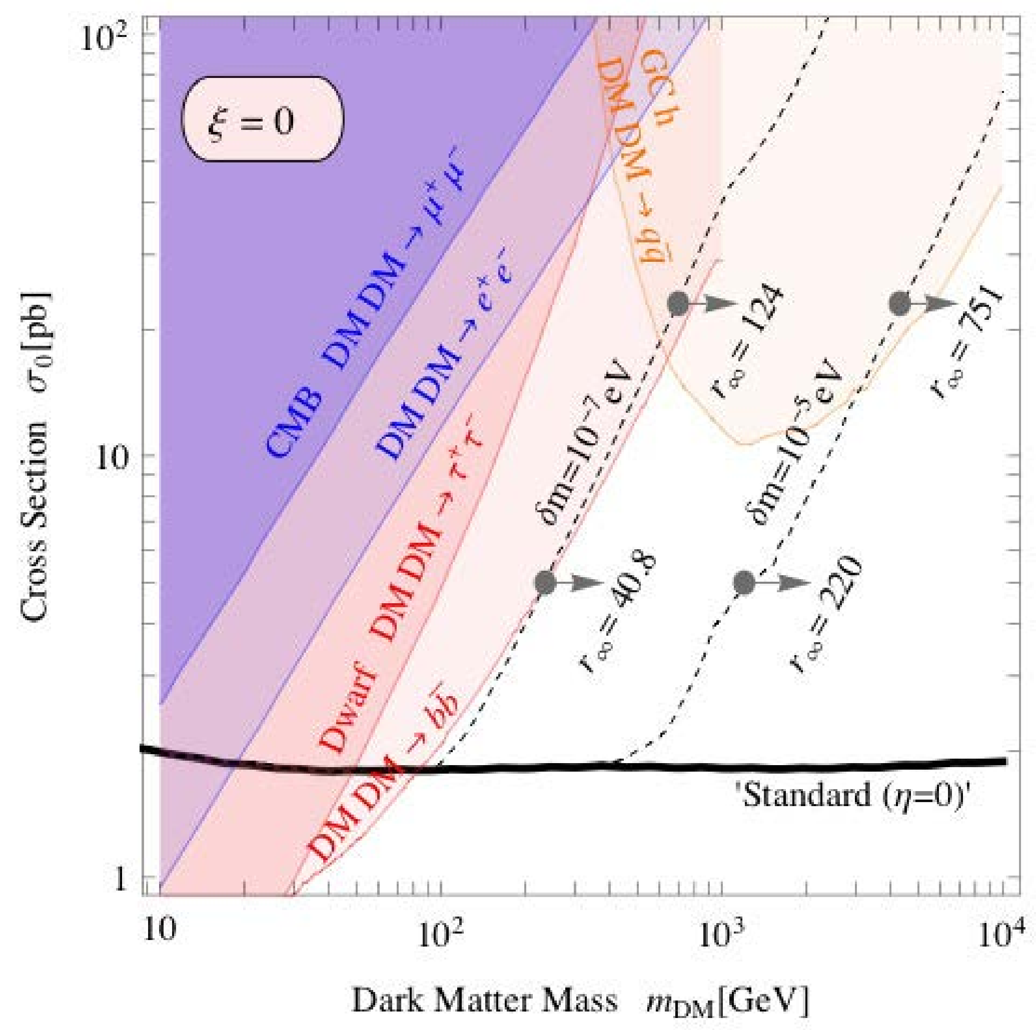
[Zentner & Hearin 11]



Asymmetric Dark Matter

Some limits including also the possibility of DM-antiDM oscillation...

[Cirelli, Panci, Servant & Zaharijas 11]



ADM @ LHC ?

Strongly model dependent…

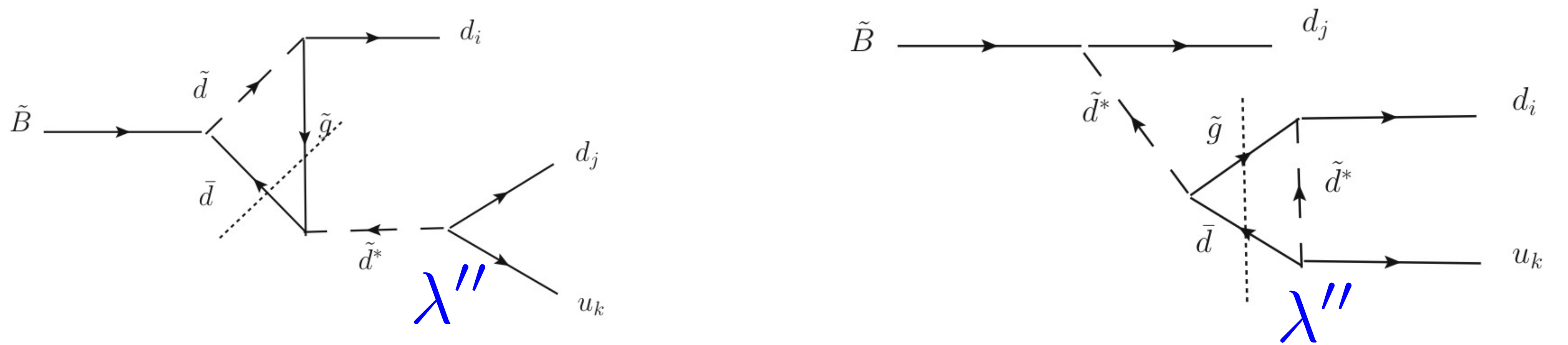
Possible to produce ADM if it interacts with colored states as possible in SUSY models, or even produce it directly if the coupling with baryons is large.

In some models ADM is connected to EW symmetry breaking, e.g. Technicolor ADM, and then a more direct influence to EW sector is also viable.

Baryogenesis in RPV SUSY

[Sundrum & Cui 12, Cui 13, Rompineve 13, ...]

Realization of good old baryogenesis via out-of-equilibrium decay of a superpartner, possibly WIMP-like, e.g. in the model by Cui with Bino decay via RPV B-violating coupling.



CP violation arises from diagrams with on-shell gluino lighter than the Bino. To obtain right baryon number the RPC decay has to be suppressed, i.e. due to heavy squarks, the RPV coupling large and the Bino density very large...

Baryogenesis & SW DM

[Arcadi, LC & Nardecchia 1312.5703]

In such scenario it is also possible to get gravitino DM via the SuperWIMP mechanism and the baryon and DM densities can be naturally of comparable order due to the suppression by the CP violation and Branching Ratio respectively...

$$\Omega_{\Delta B} = \frac{m_p}{m_\chi} \epsilon_{\rm CP} BR\left(\chi \to \not{B}\right) \Omega_\chi^{\tau\to\infty}$$

Small numbers

$$\Omega_{\rm DM} = \frac{m_{\rm DM}}{m_\chi} \boxed{BR\left(\chi \to DM + \text{anything}\right)} \Omega_\chi^{\tau\to\infty}$$

$$\rightarrow \quad \frac{\Omega_{\Delta B}}{\Omega_{\rm DM}} = \frac{m_p}{m_{\rm DM}} \epsilon_{\rm CP} \frac{BR\left(\chi \to \not{B}\right)}{BR\left(\chi \to DM + \text{anything}\right)}$$

independent of Bino density

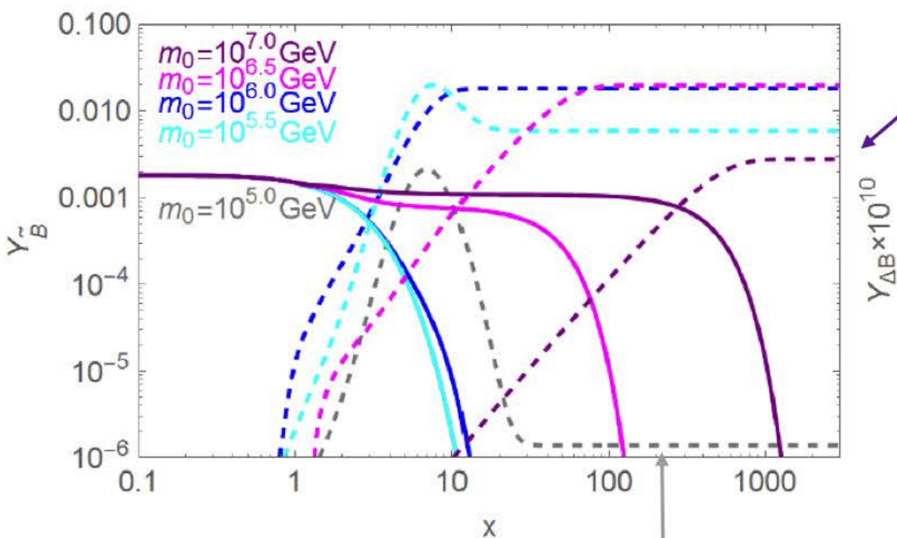
Gravitino DM: BR is naturally small and DM stable enough !

Baryogenesis in RPV SUSY

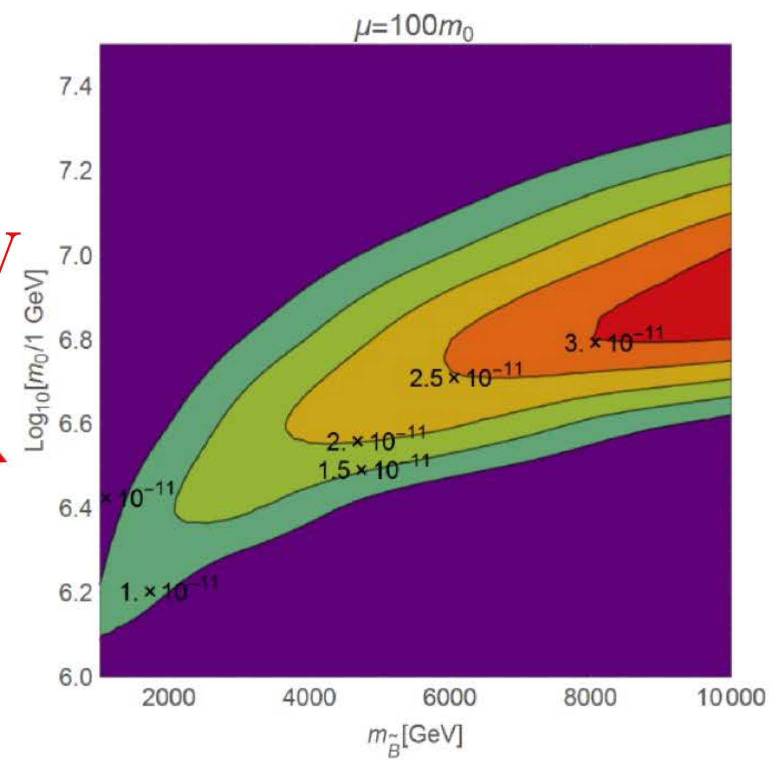
[Arcadi, LC & Nardecchia 1507.05584]

Unfortunately realistic models are more complicated than expected: wash-out effects play a very important role !!!

Asymmetry suppressed by the high scalars



10^7GeV



Asymmetry suppressed by wash-out

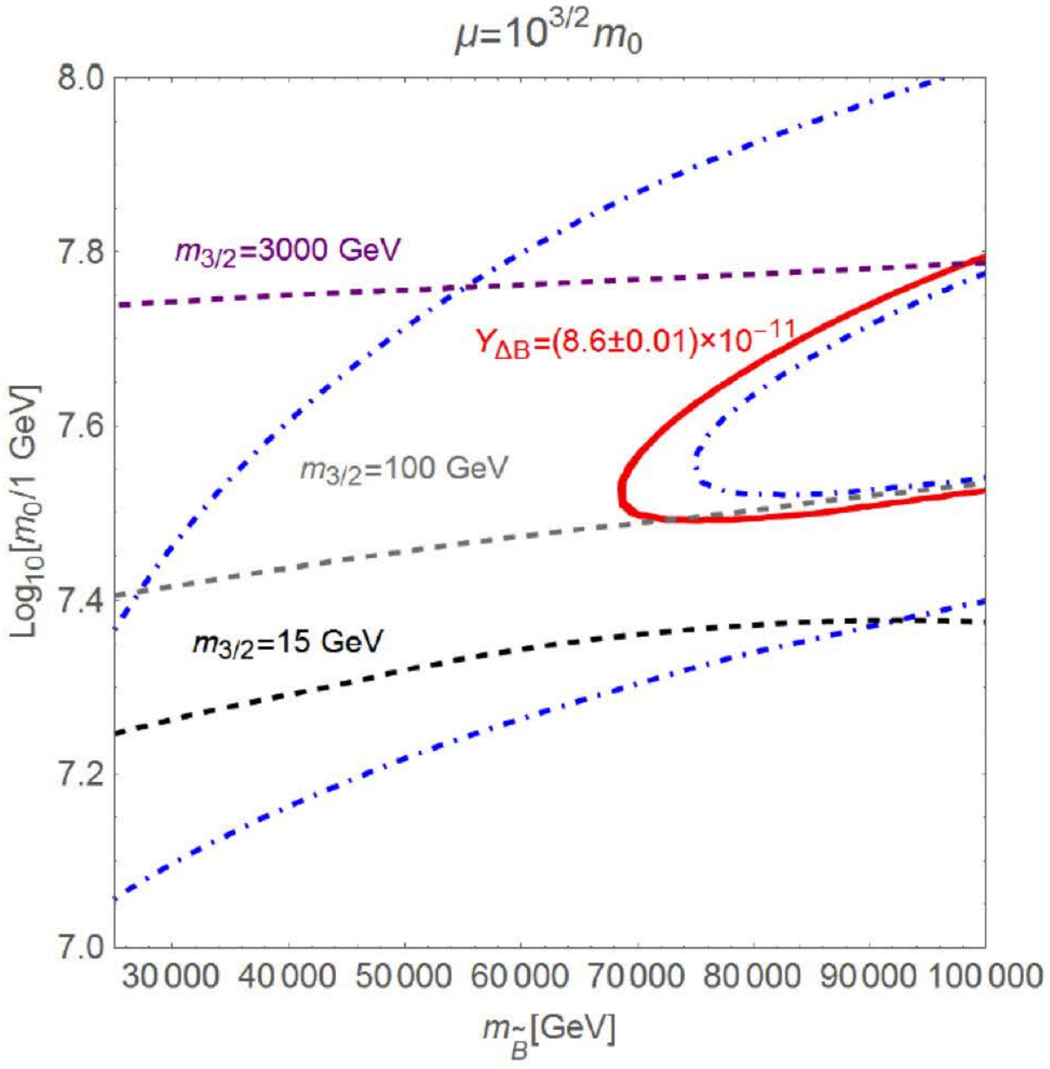
Rather definite prediction for range of scalar masses

Heavy !!!

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

But the large scalar mass increases the branching ratio into gravitinos... Need a pretty large gravitino mass to compensate !



Correct baryon density compatible with DM relic density for gravitino masses O(100 GeV-few TeV)

$$\Gamma\left(\tilde{\psi}_{3/2} \to udd\right) = N_c \frac{\lambda^2}{6144\pi^3} \frac{m_{3/2}^7}{m_0^4 M_{\rm Pl}^2}$$

$$\tau_{3/2} \approx \frac{4.6}{N_c} \times 10^{28}{\rm s}\left(\frac{\lambda}{0.4}\right)^{-2}\left(\frac{m_0}{10^{7.5}{\rm GeV}}\right)^4\left(\frac{m_{3/2}}{1{\rm TeV}}\right)^{-7}$$

Lifetime of the gravitino within the sensitivity of AMS.

Gluino NLSP in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

The gluino is in this scenario the lightest SUSY particle and may be produced at colliders; but it should be not too much lighter than the Bino, i.e. $m_{\tilde{g}} \sim 0.1 - 0.4\, m_{\tilde{B}} \sim 7 - 28$ TeV, possibly in the reach of a 100 TeV collider.

$$c\tau_{\tilde{g}} \sim 1,5 \text{ cm} \left(\frac{\lambda''}{0.4}\right)^{-2} \left(\frac{m_0}{4 \times 10^7 \text{GeV}}\right)^4 \left(\frac{m_{\tilde{g}}}{7 \text{ TeV}}\right)^{-5}$$

The heavy squarks give displaced vertices for the gluino decay via RPV, even for RPV coupling of order 1.
Gluino decay into gravitino DM is much too suppressed to be measured.

Conclusions & Outlook

- The baryon asymmetry of the Universe is jet an unsolved puzzle !
- Different mechanisms can explain it, MOSTLY based on physics beyond the Standard Model !
- Basic ingredients for baryogenesis: CP violation and deviation from thermal equilibrium, therefore not always easy to compute...
- Few mechanisms are connected to the EW scale/ phase transition and are being tested at the LHC, in particular EW baryogenesis, but some also happen at high scale and are less testable.