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Baryogenesis in the Early Universe

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$[q, p] = i\hbar$

invisibles
neutrinos, dark matter & dark energy physics

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

Outline

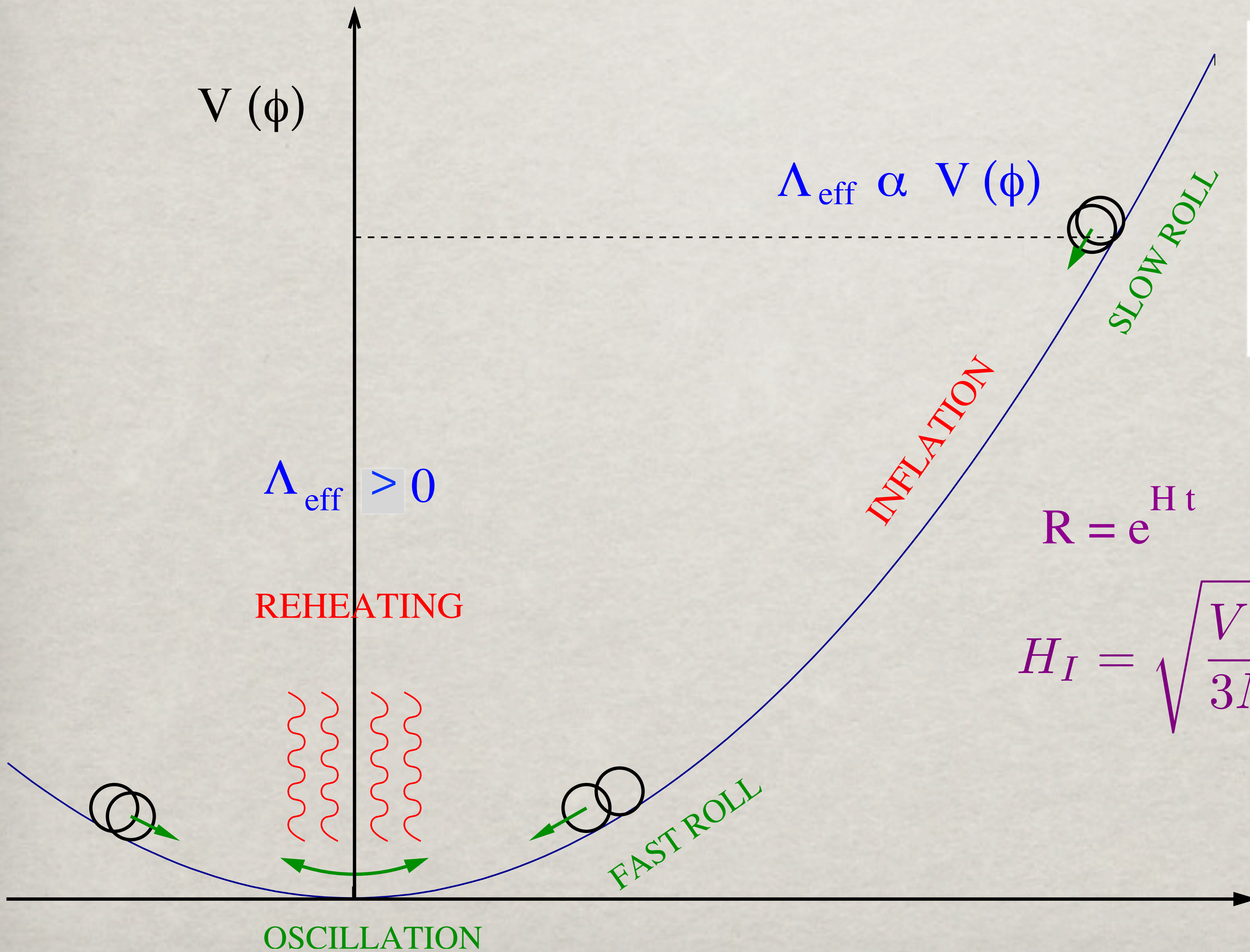
- Lecture I: Basics
- Lecture II: ElectroWeak Baryogenesis
- Lecture III: Leptogenesis
- Lecture IV: Affleck-Dine, etc...
- Outlook

Outline

- Introduction:
  Scalar fields in the early Universe
- Affleck-Dine Baryogenesis
- Cold EW Baryogenesis
- Asymmetric Dark Matter
- Outlook

Scalar Fields in the Universe

Inflation: driven by a scalar field ϕ



$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$|\eta| = \left|\frac{V''}{V}\right| \ll 1$$

$R = e^{H t}$ Quasi - de Sitter

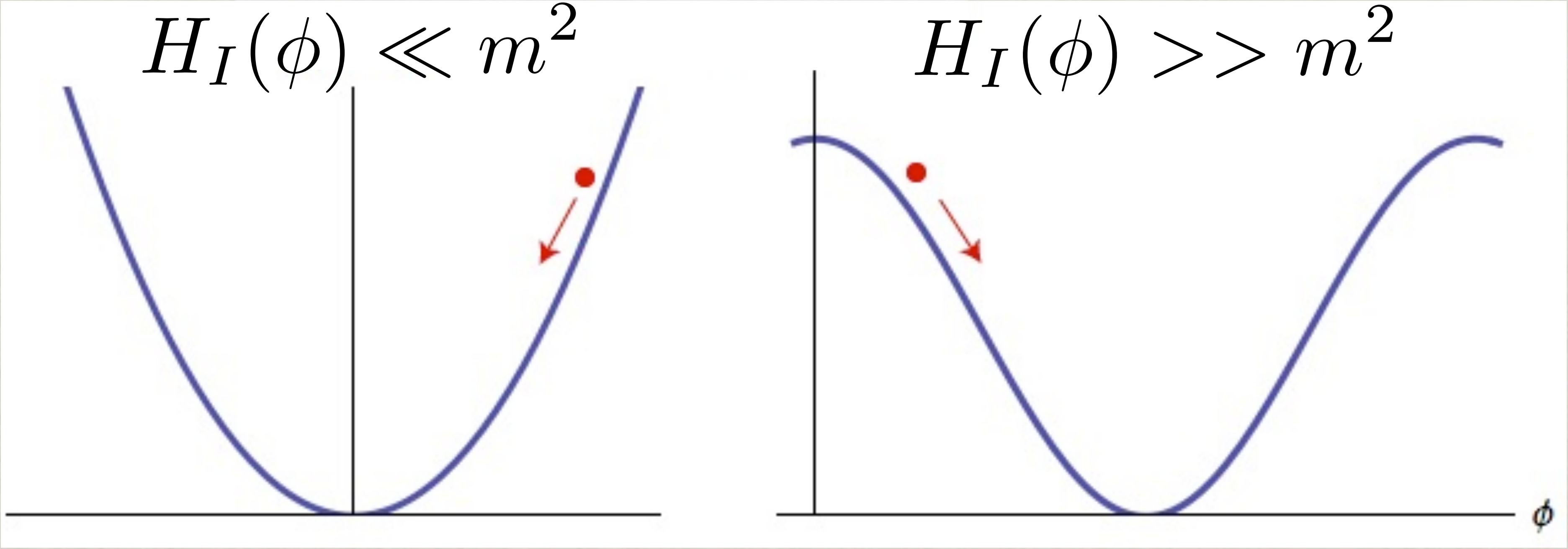
$$H_I = \sqrt{\frac{V(\phi)}{3M_P^2}}$$

de Sitter ?

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.

Light Field in cosmology

Apart for the classical motion, for light fields there are also quantum fluctuations:

$$\phi = \varphi_c + \delta\varphi$$

In an inflationary (de Sitter) phase these are given by

$$\delta\varphi = \frac{H}{2\pi}$$

They can survive after inflation and generate isocurvature perturbations !!!

Scalar field in de Sitter

For the quantum fluctuation of the field $\phi = \varphi_c + \delta\varphi$

in an inflationary (de Sitter) phase the field equation is

$$\delta\ddot{\varphi} - \nabla\delta\varphi + 3H\delta\dot{\varphi} + V''(\phi)\delta\varphi = 0$$

In conformal time & Fourier space, rescaling the field, one has

$t \to \eta = -1/aH \qquad ' \to d/d\eta \qquad u_k = \delta\varphi_k/a$

$$u_k'' + \left(k^2 + V''(\phi)a^2 - \frac{a''}{a}\right)u_k = 0$$

Usually the potential term is negligible and $\dfrac{a''}{a} \sim H^2a^2$

Harmonic oscillator with negative time-dependent mass !

Affleck-Dine baryogenesis

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

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

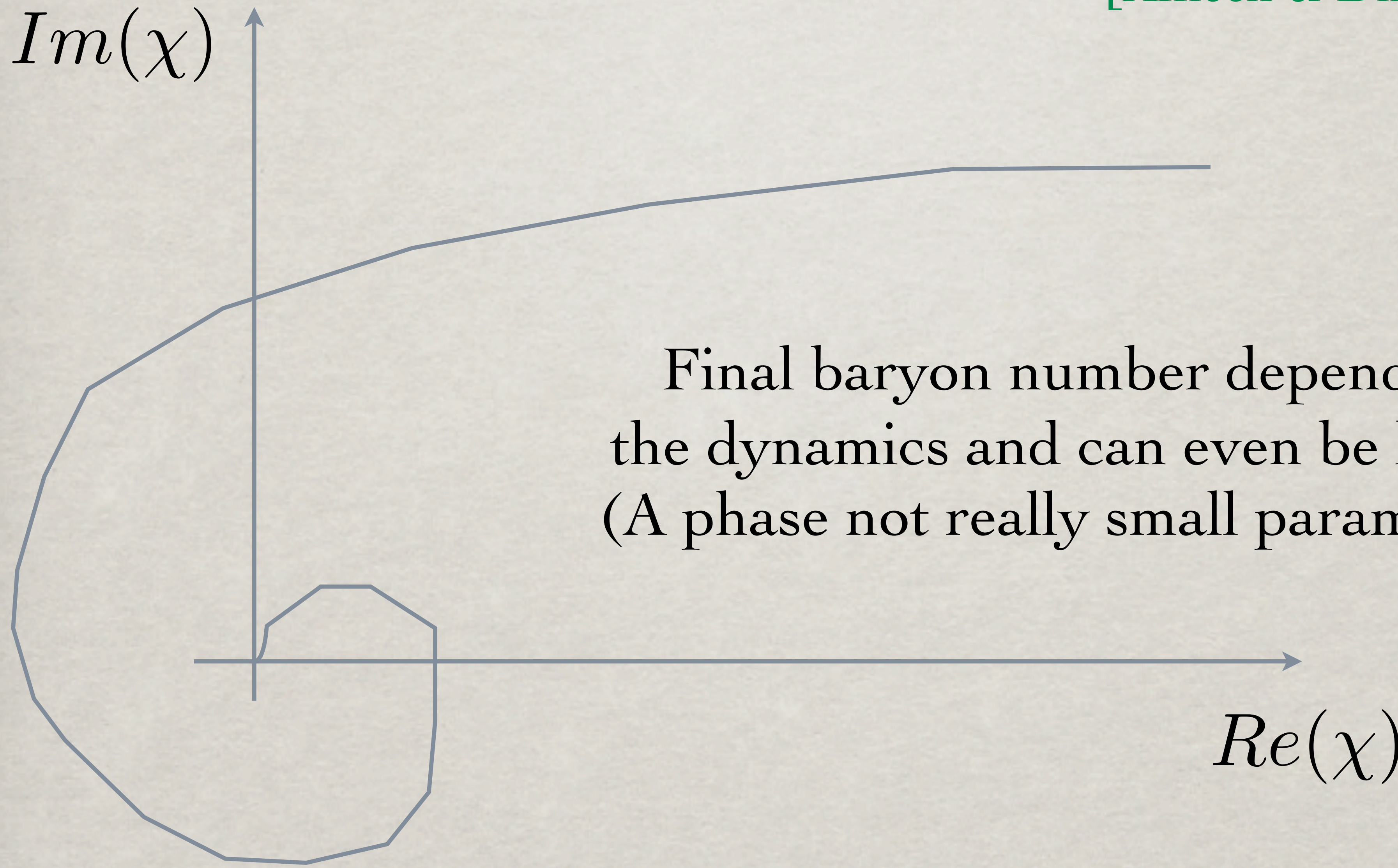
during inflation ($H_I >> m_{3/2}$) the v.e.v. sets at a large scale, while it relaxes later to the minimum at 0

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

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

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

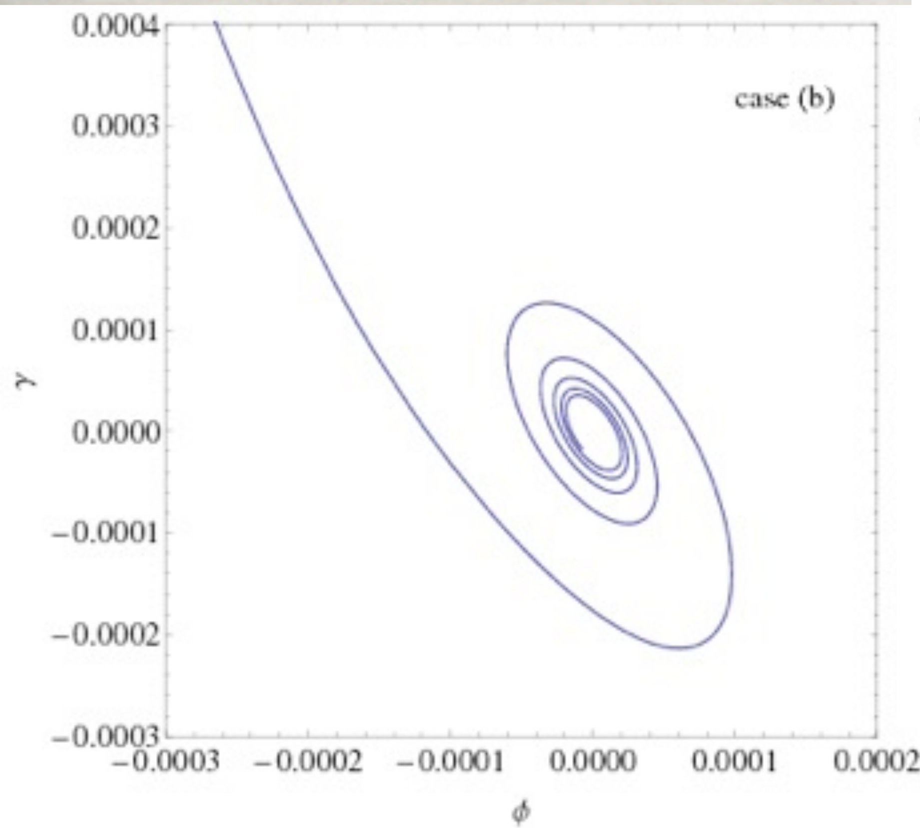
The main effect arises for large v.e.v of the field !
The value can oscillate with χ and it is transferred to fermions at the time the condensate decays:

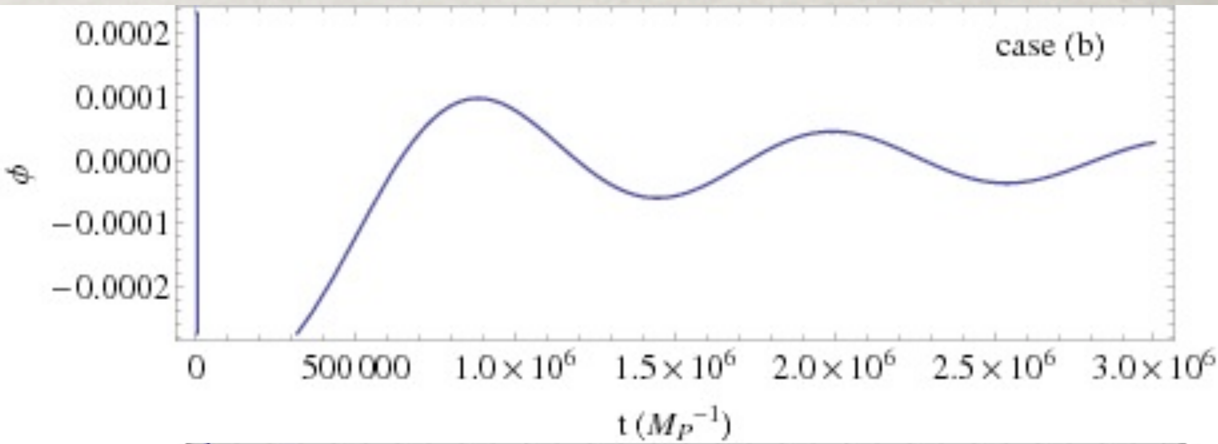
$$Y_B = \frac{n_b}{n_\chi} \frac{T_{RH} \rho_\chi}{m_{3/2} \rho_\phi} \sim 10^{-10} \left(\frac{T_{RH}}{10^6 \mathrm{GeV}} \right) \left(\frac{10^{-3}}{\lambda} \right)$$

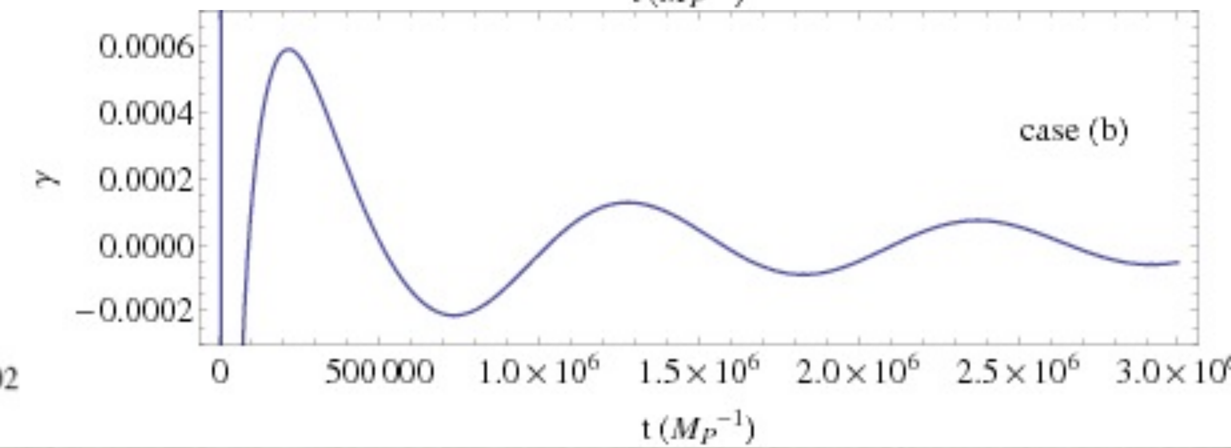
AD Baryogenesis in SUGRA

[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



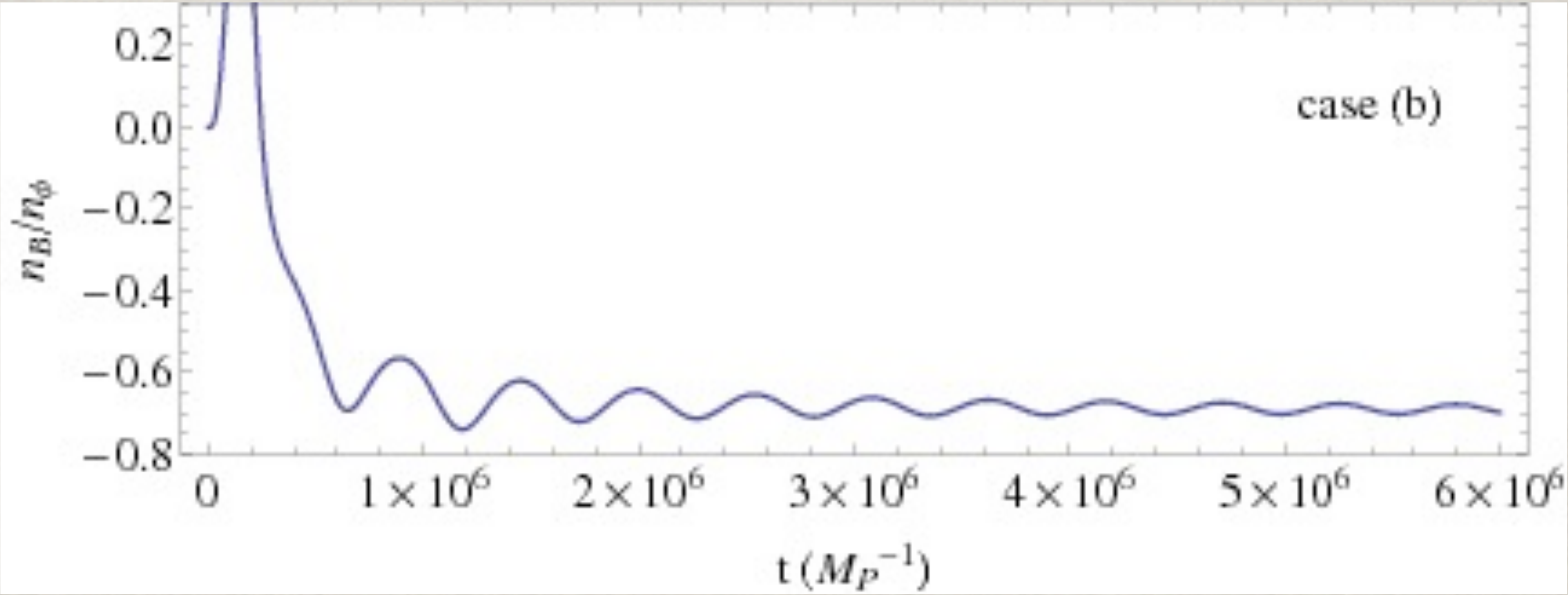




AD Baryogenesis in SUGRA

[Garcia & Olive '13]

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

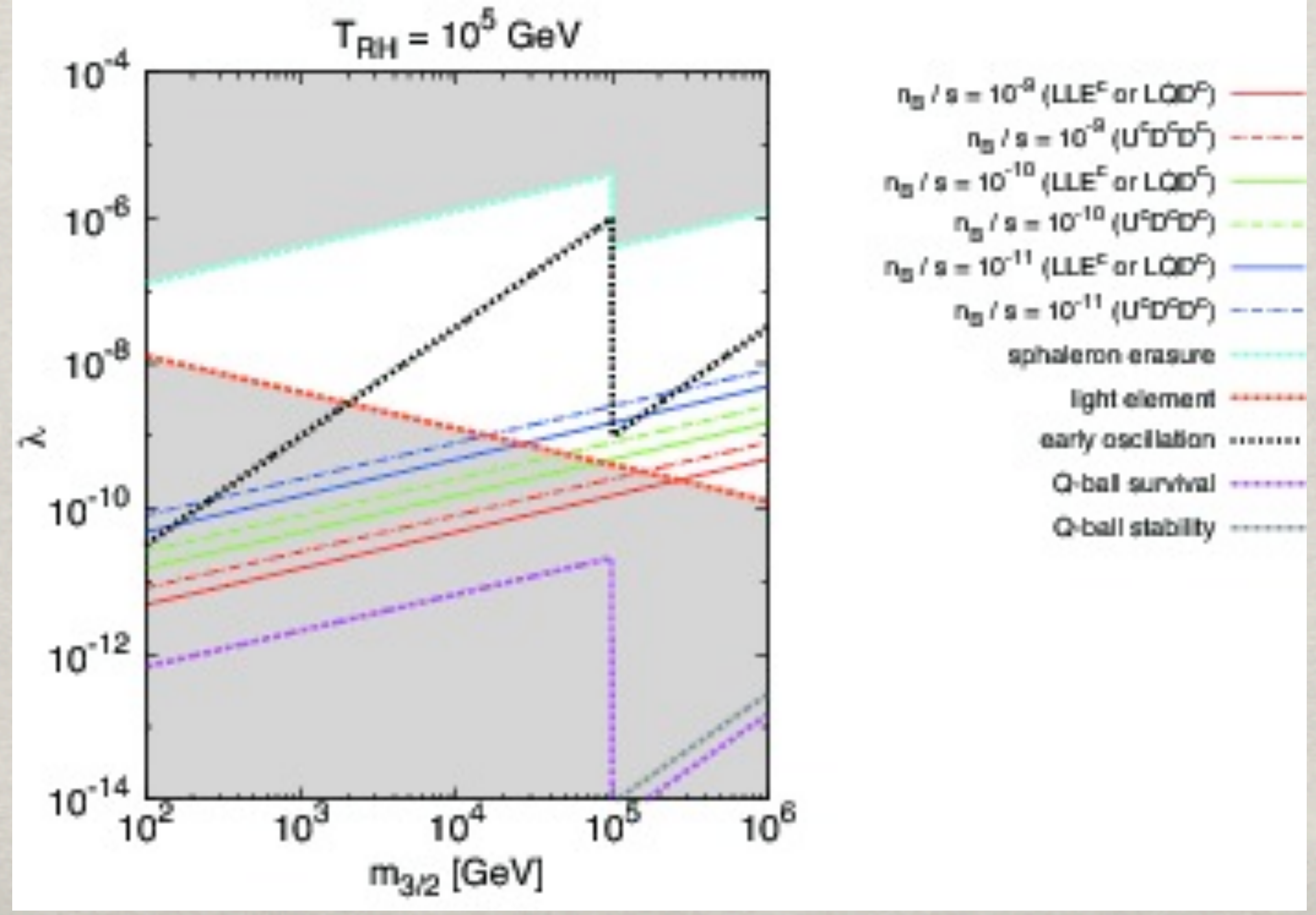


In this case need sufficiently high T_RH to allow for sphaleron processes to reprocess L into B

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.

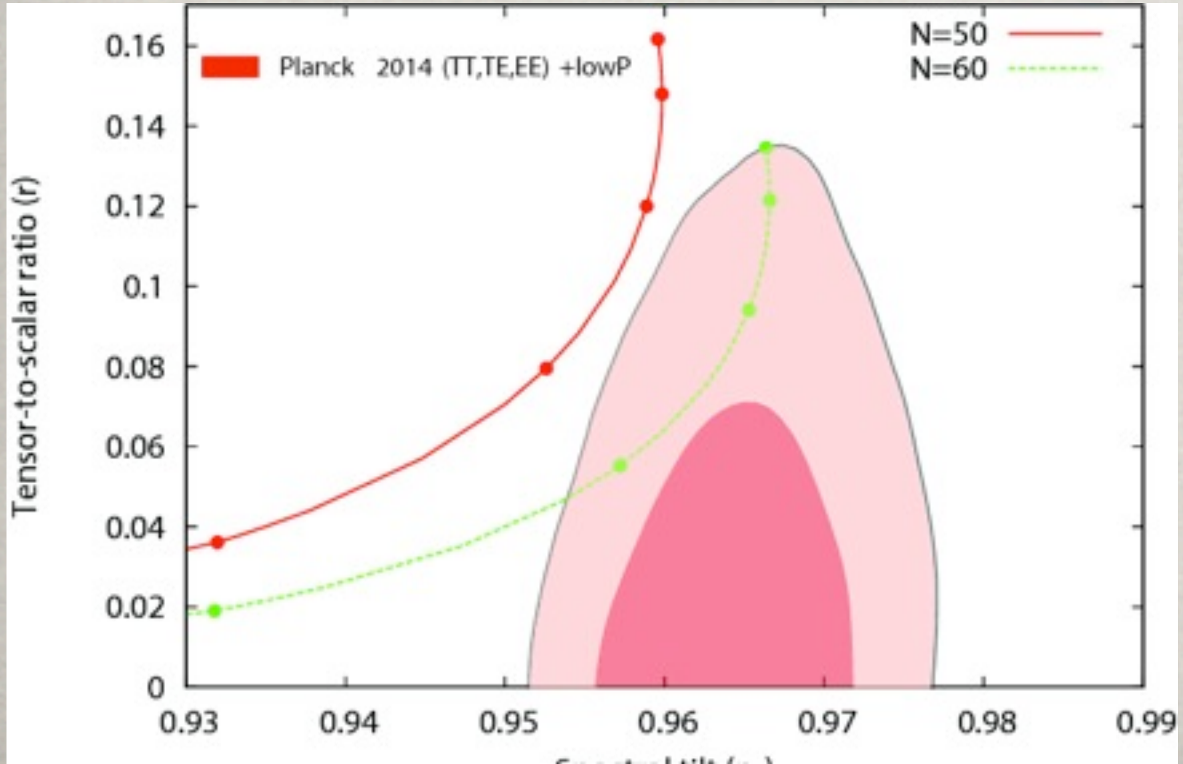


AD sneutrino inflation

[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

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

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

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

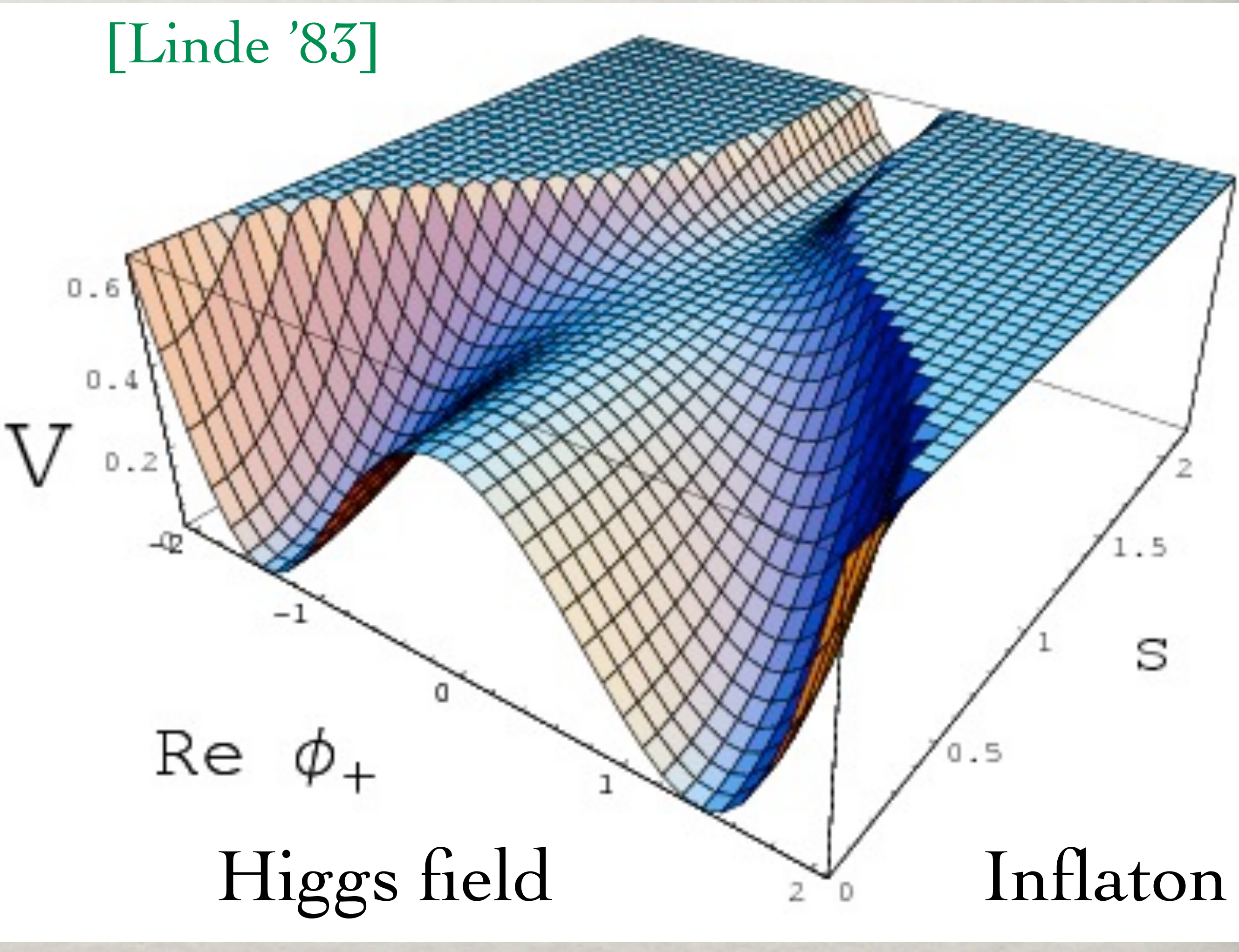
COLD EW BARYOGENESIS

Cold EW Baryogenesis

[J. Garcia-Bellido et al '99, Krauss & Trodden '99, Felder et al '00, van Tent at al]

Hybrid inflation

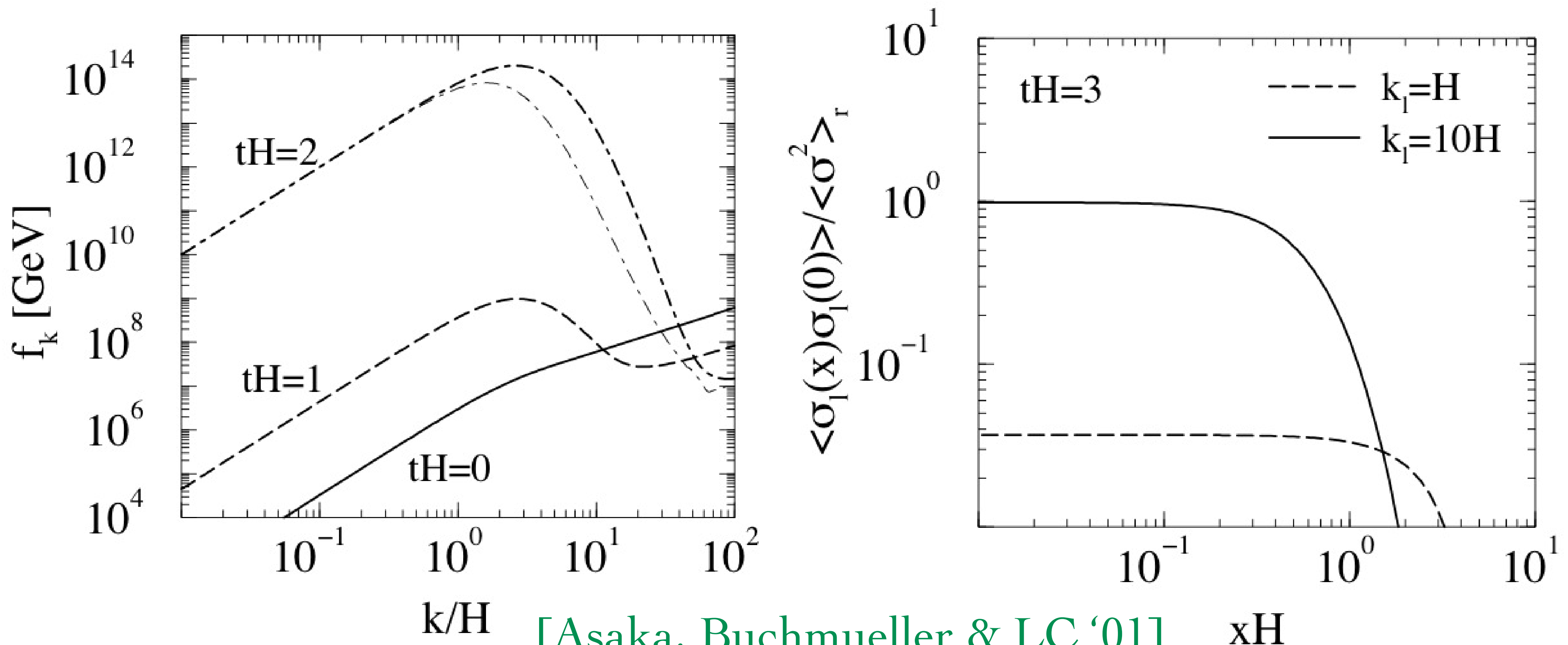
Cold EW baryogenesis is based on an EW phase transition which is not driven by temperature, but by another field, in a hybrid inflation setting.



Tachyonic instability

At the critical value of the inflaton field, the Higgs field mass changes sign and a tachyonic instability takes place.

Low momentum modes start to grow exponentially and the Universe breaks down in domains of size 1/H



[Asaka, Buchmueller & LC '01]

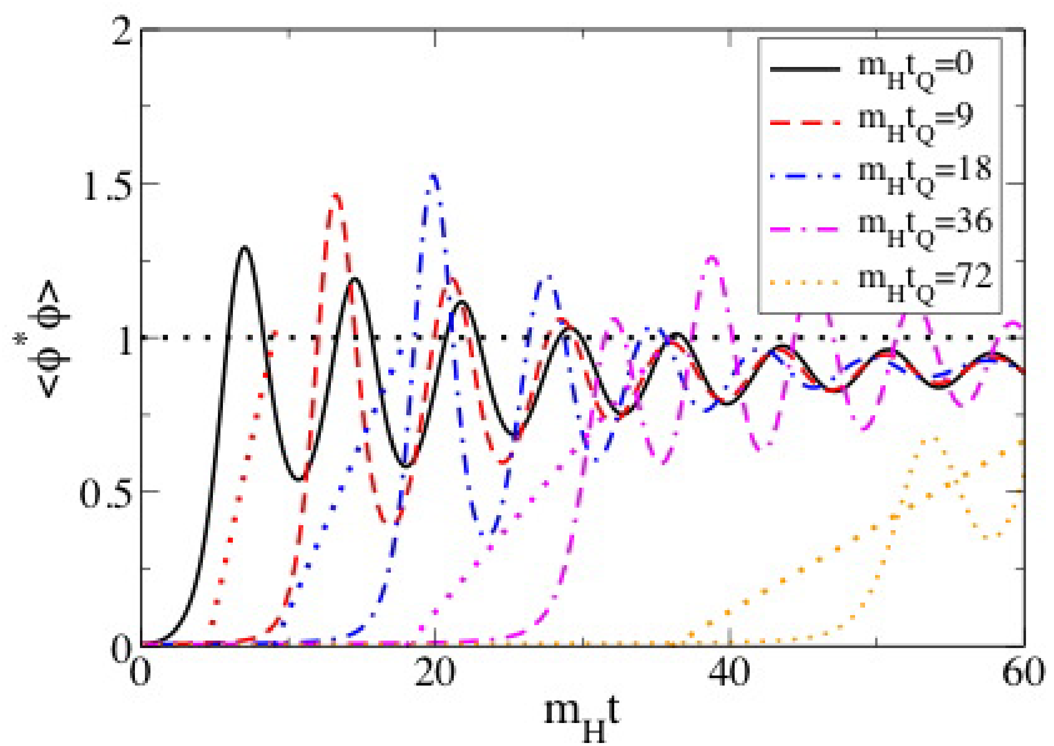
Cold EW Baryogenesis

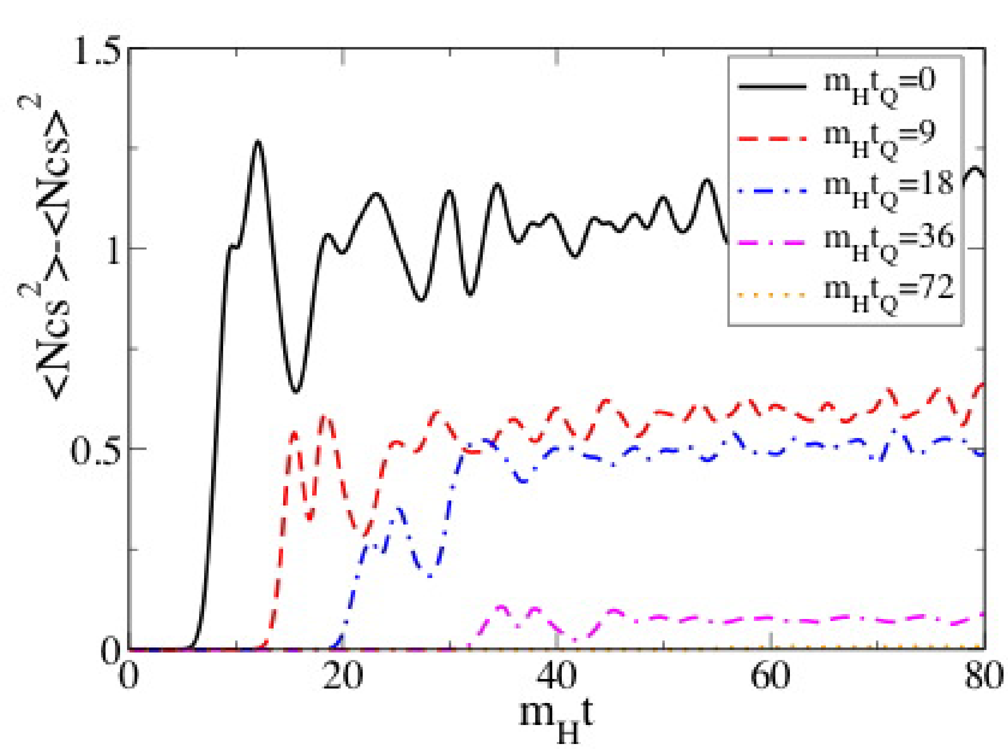
[Transberg& Smit '03, Transberg, Smit & Hindmarch '06]

Beyond the initial stages, analytical computations not possible.

Discretize the action on the lattice and solve the classical equation of motions for Higgs+gauge field in real time !

The Higgs field/gauge configurations obtain a non-trivial winding/Chern-Simons number: key parameter is quench time.





COLD EW BARYOGENESIS

[Transberg& Smit '03, Transberg, Smit & Hindmarch '06]

CP violation is provided by the effective coupling of the Higgs to the gauge fields, giving rise to a chemical potential for N_{CS}.

$$\int d^4x\, \kappa\phi^\dagger\phi \mathrm{Tr}\, F\tilde{F} \leftrightarrow -\int dt\, \mu_{\rm ch} N_{\rm cs}, \quad \mu_{\rm ch}(t) = \frac{3\delta_{\rm cp}}{m_W^2}\frac{d}{dt}\langle\overline{\phi^2}(t)\rangle.$$

The Baryon asymmetry is generated through the anomaly coupling between the B current and

$$\partial_\mu j^\mu_B = \frac{1}{16\pi^2}\left[F_{\mu\nu}\tilde{F}^{\mu\nu}\right] \longrightarrow B = 3\langle N_{CS}(t) - N_{CS}(0)\rangle$$

Final result depends on the quench-time and CP phase δ_{CP}

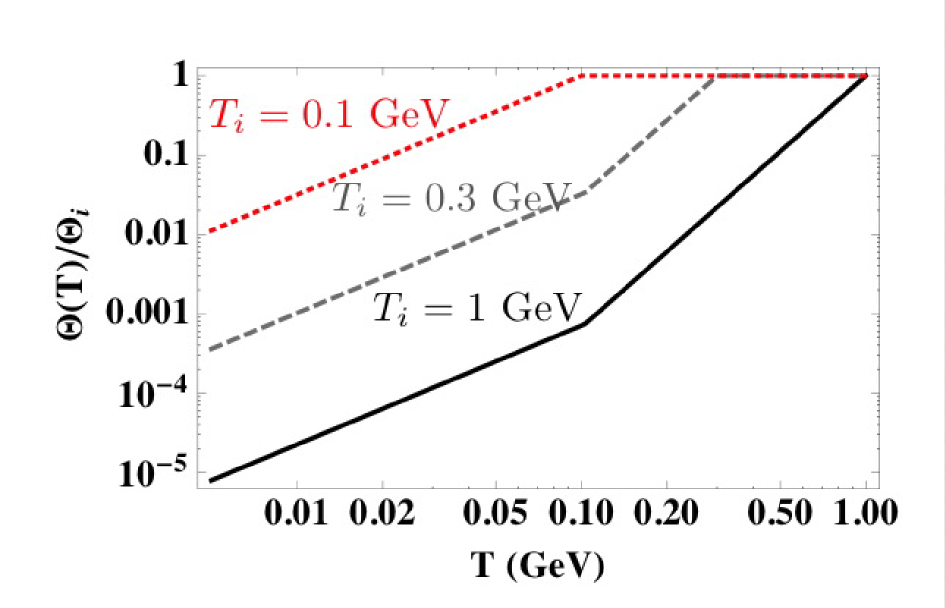
Note: Sphalerons cannot erase B since they are no more effective, since the "effective" temperature is lower than T_{EW}

Cold EW Baryogenesis

[G. Servant '13]

Recent twist in the story: CP violation could also be provided by an axion field instead and by the strong anomaly !

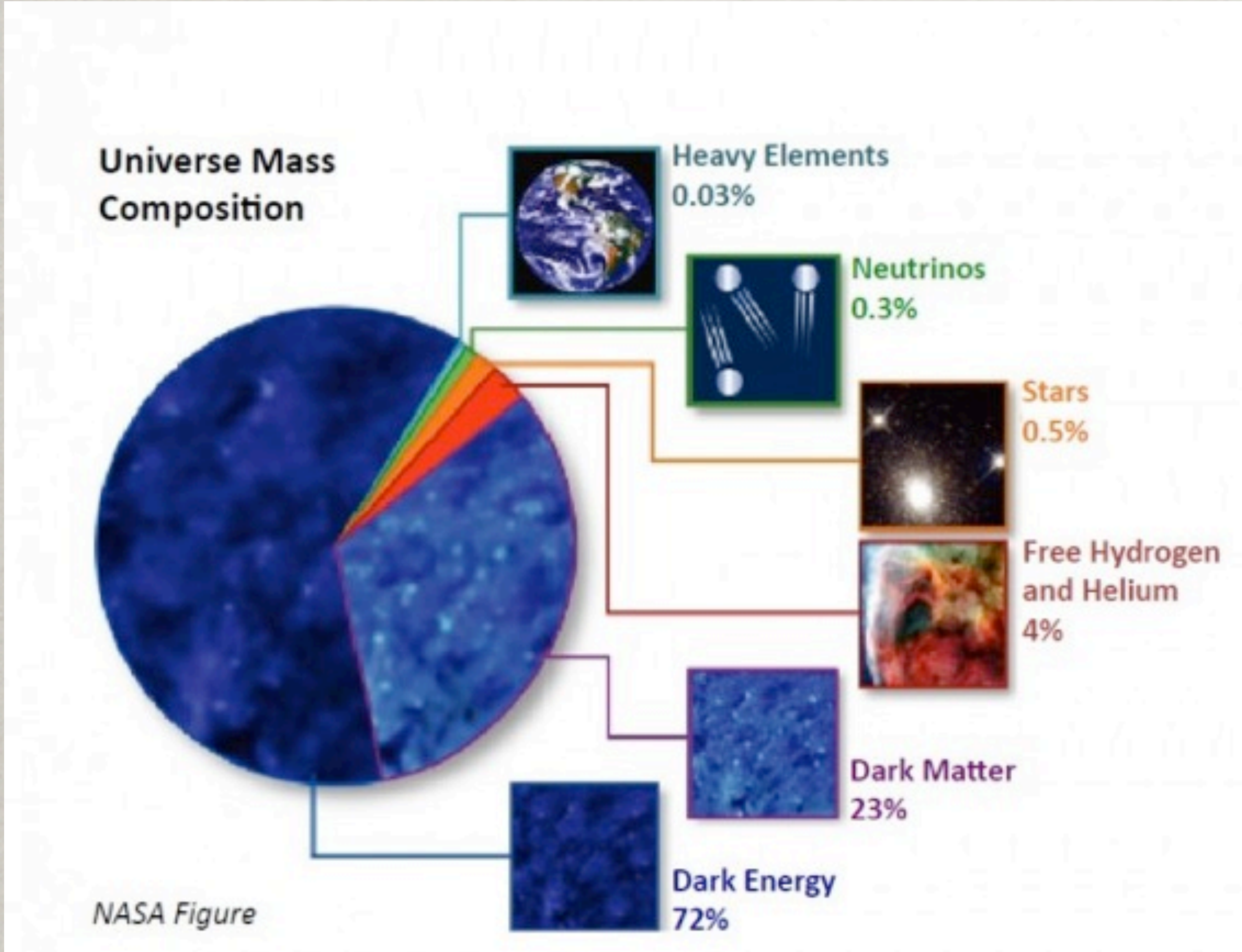
$$\frac{\alpha_s\ a(x)}{8\pi f_a} tr\left[G_{\mu\nu}\tilde{G}^{\mu\nu}\right]$$



A time dependence on a(x) is needed and therefore the EW phase transition has to be delayed at the time of the QCD phase transition. The CP violation is transferred to the EW sector through an effective gluon-EW gauge boson coupling.

Asymmetric Dark Matter

Universe composition



$$\Omega_{DM} \sim 5\,\Omega_B$$

Why so many components with similar densities ???

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.

$$\Psi \to B + X$$

$$n_{DM} \sim n_b \to \Omega_{DM} \sim 5\,\Omega_b$$
$$\text{for } m_{DM} \sim 5\,m_p = 5\,\text{GeV}$$

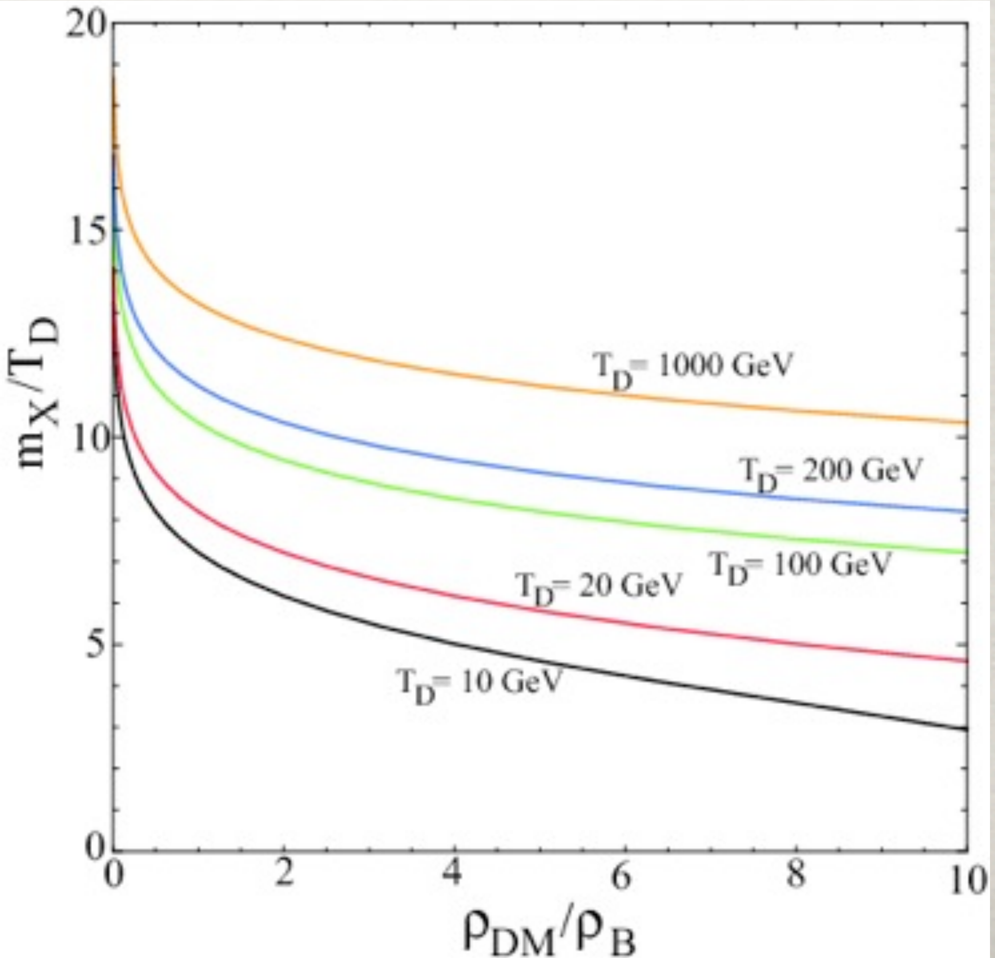
The puzzle of similar densities can be given by similar masses !

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:

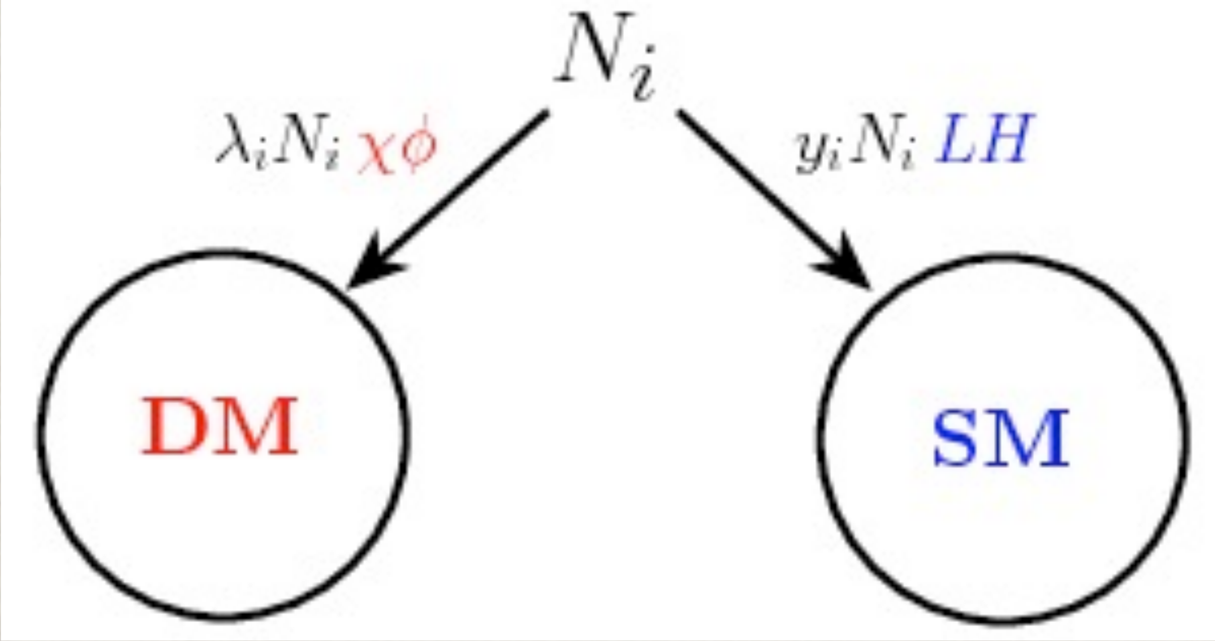
DM Mass/
T_Decoupling



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

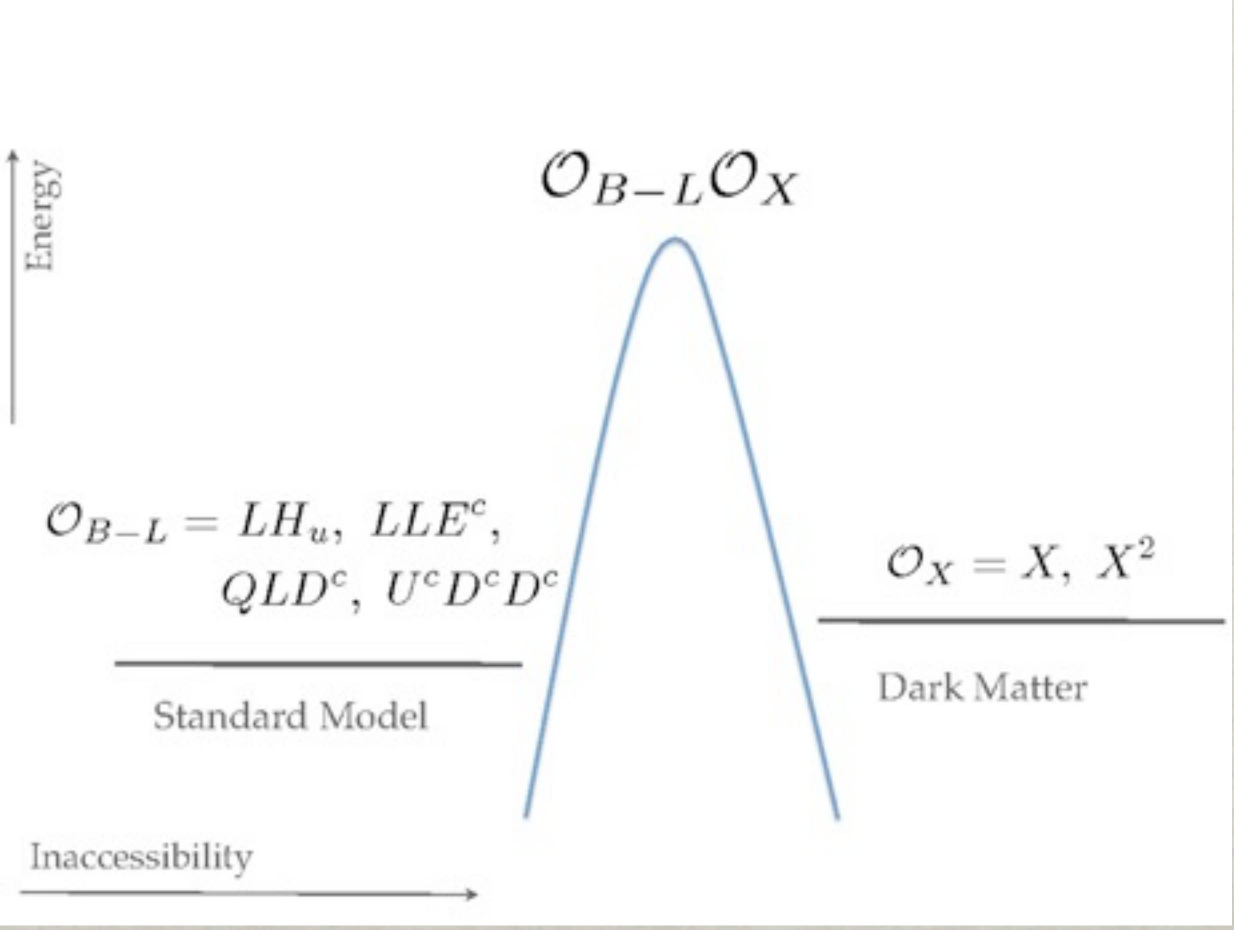


Need similar CP violation in both sectors !

Asymmetric Dark Matter

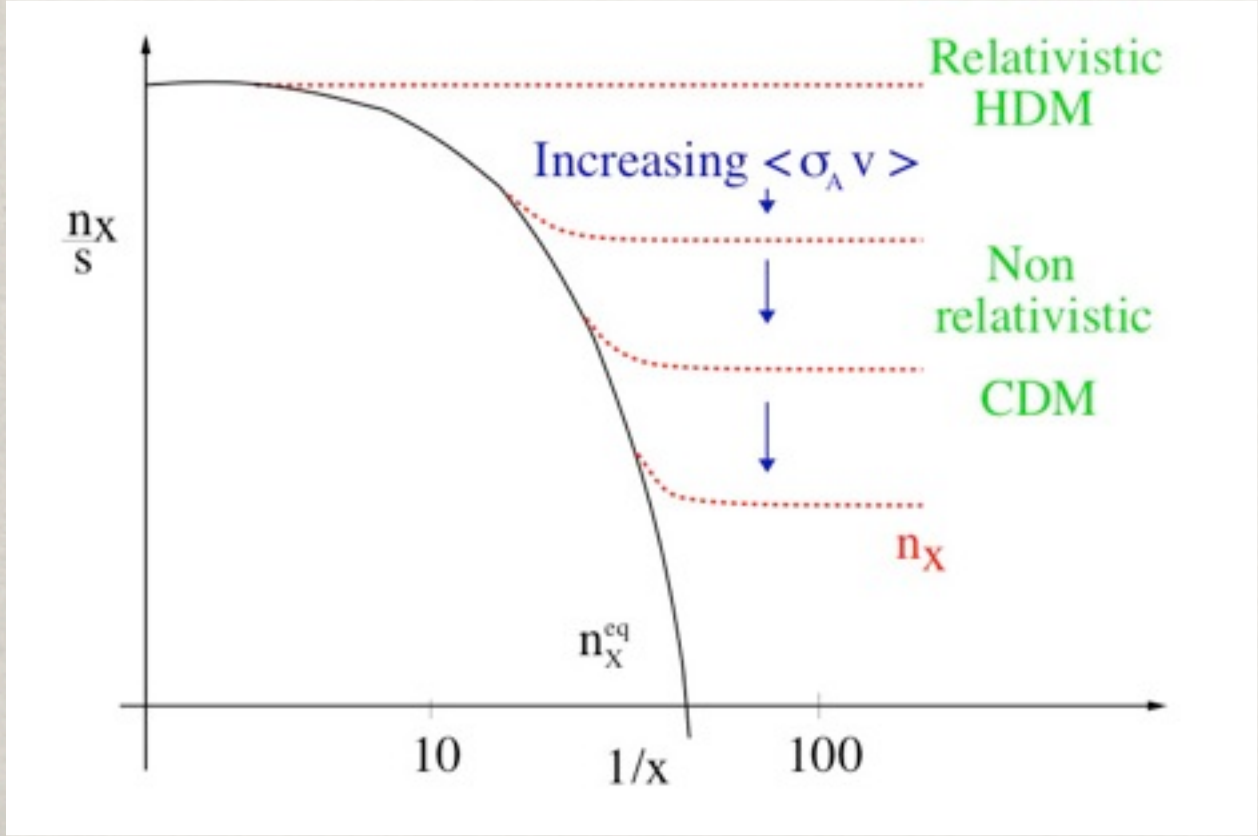
[Griest & Seckel '87, Kaplan, Luty &Zurek 90, ...]

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...



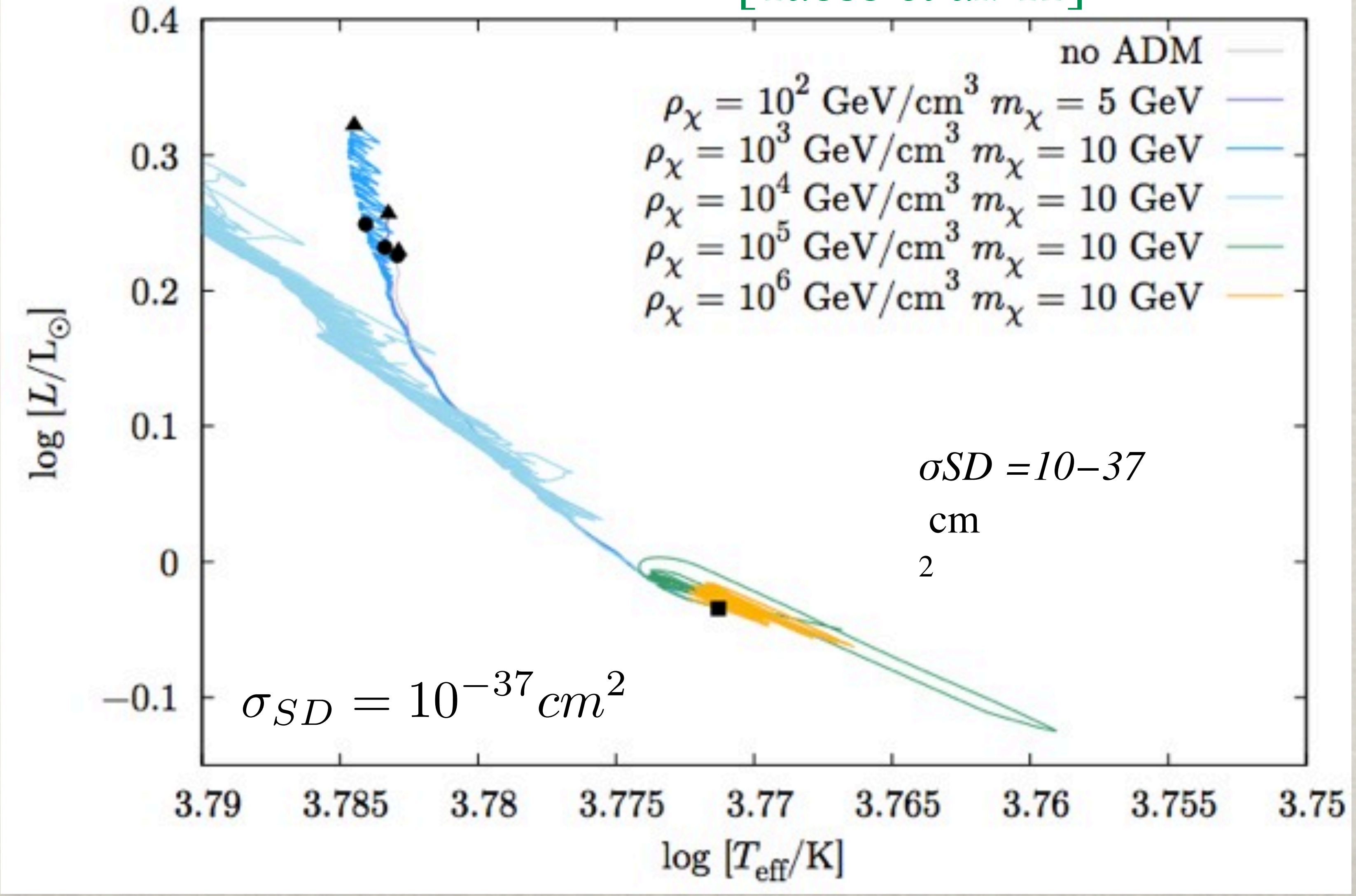
Strong coupling...
...like baryons !

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...

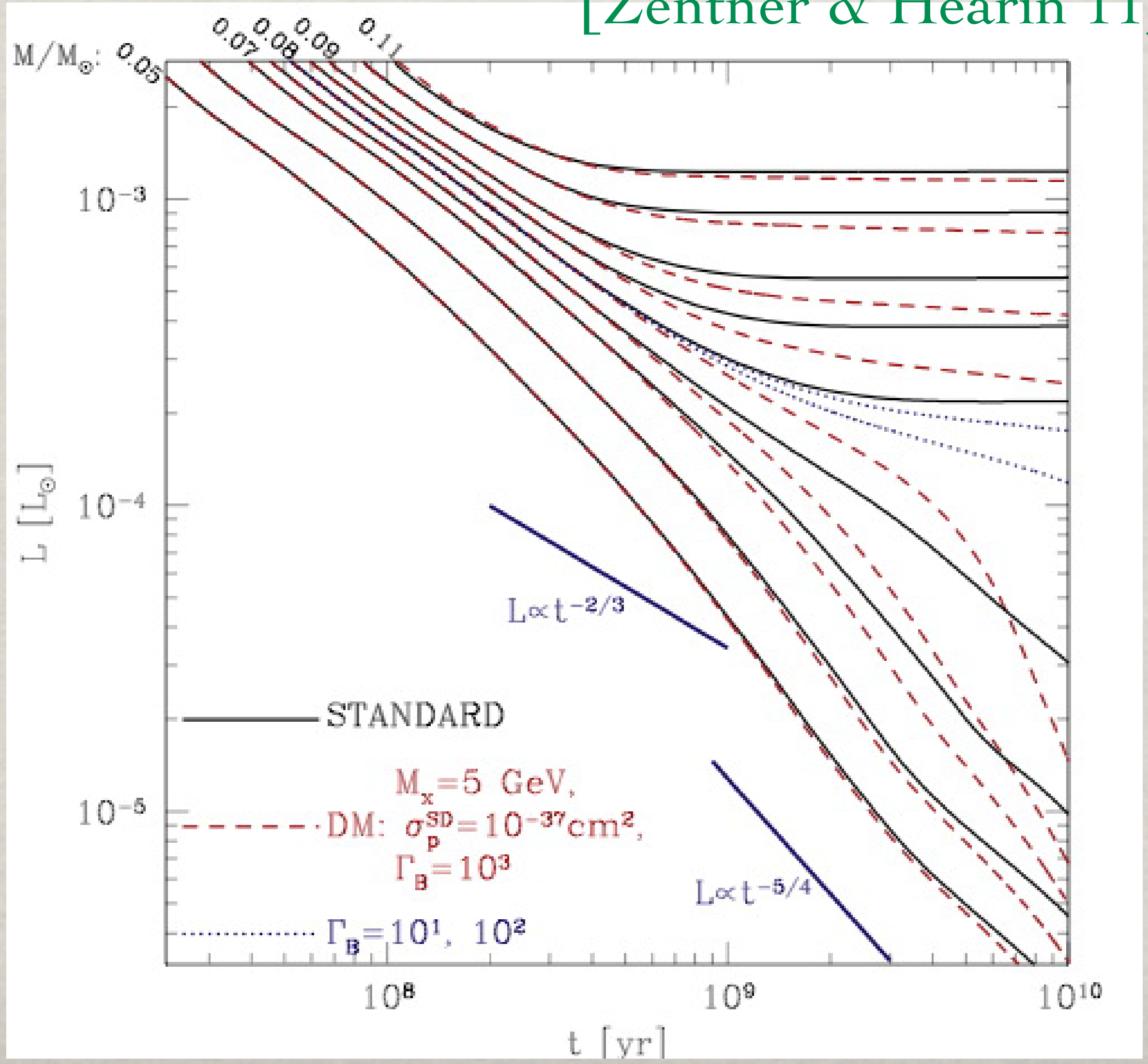
[Taoso et al. 12]



Asymmetric Dark Matter

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

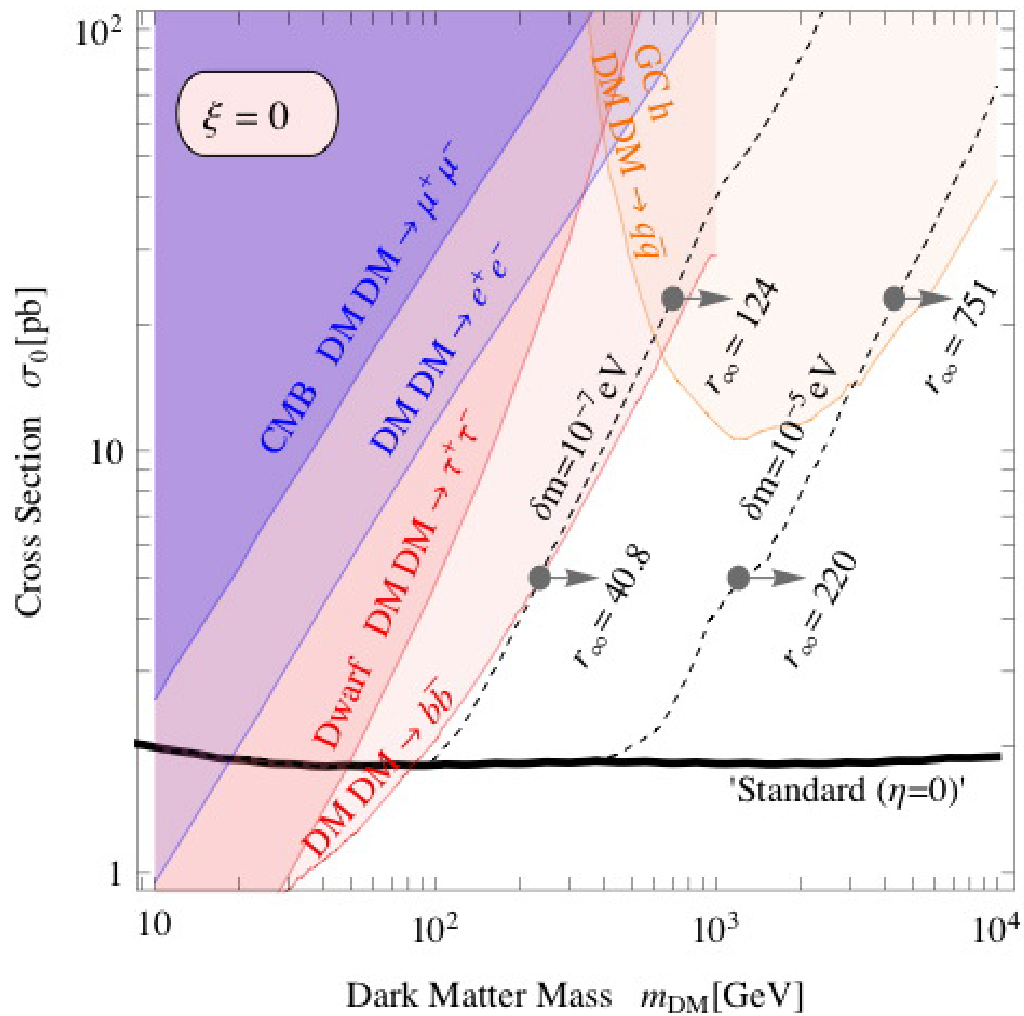
[Zentner & Hearin 11]



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.

Outlook

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 ingredient for baryogenesis: deviation from thermal equilibrium, therefore not easy to make computations...
- Few mechanisms are connected to the EW scale/ phase transition and are being tested at the LHC, in particular EW baryogenesis.

References

- I. Affleck & M. Dine - A new mechanism for baryogenesis - NPB249 (1985) 361
- A. Riotto & M. Trodden - Recent progress on baryogenesis - hep-ph/9901362
- K. Zurek - Asymmetric Dark Matter - arXiv:1308.0338