NIKHEF Theory Group Seminar 2020

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Mechanisms for the Common Origin of DM & the BAU

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$[q,p]=i\hbar$

elusiVes-inVisiblesPlus
neutrinos, dark matter & dark energy physics

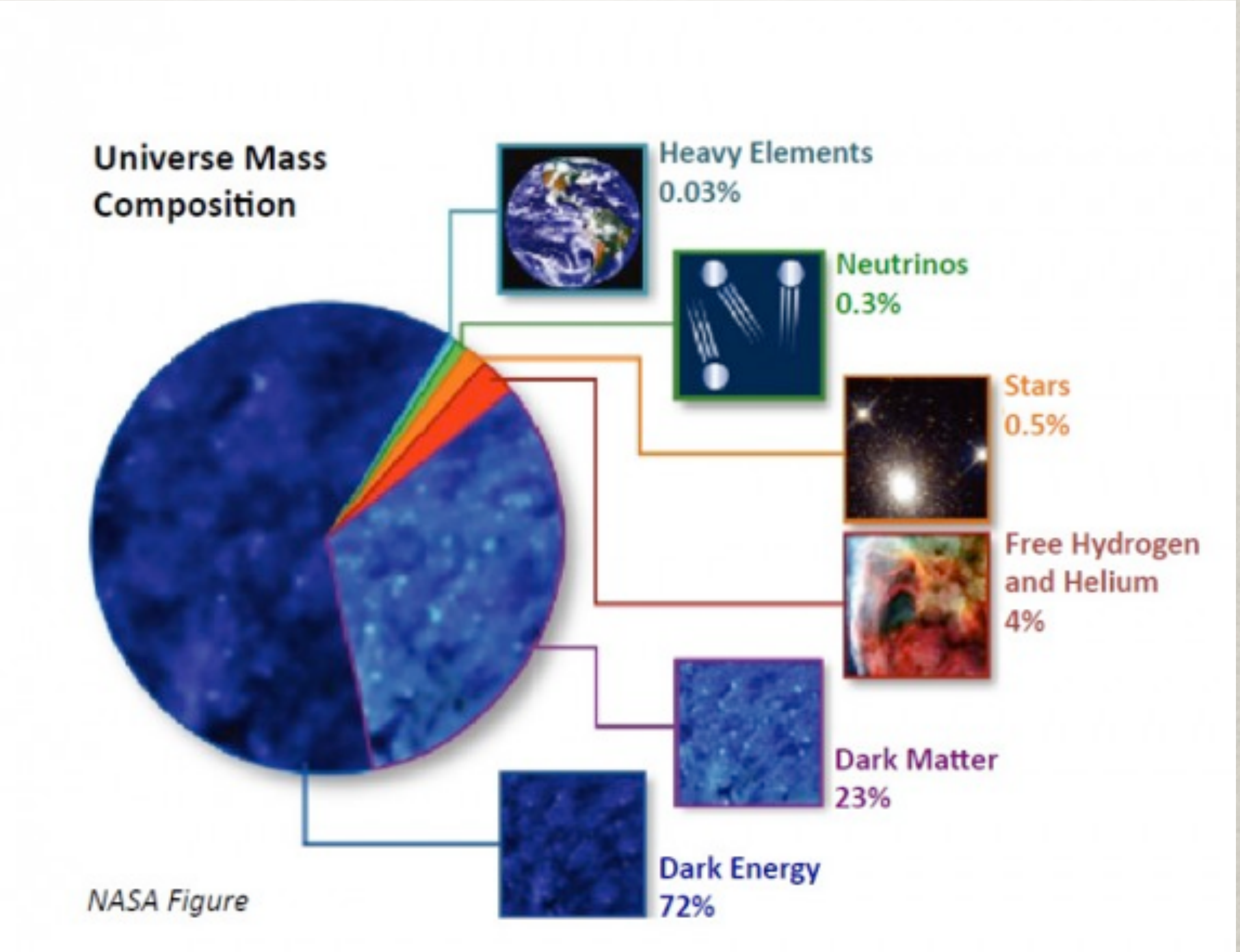
MARIE CURIE ACTIONS

Outline

- Introduction:
  Baryogenesis & CP violation
- Asymmetric DM:
  a minimal model for DM, neutrino masses and leptogenesis
- (Sommerfeld enhancement at finite T)
- Co-genesis:
  Baryogenesis and DM from RPV
- Outlook

Baryogenesis & CP violation

Universe composition

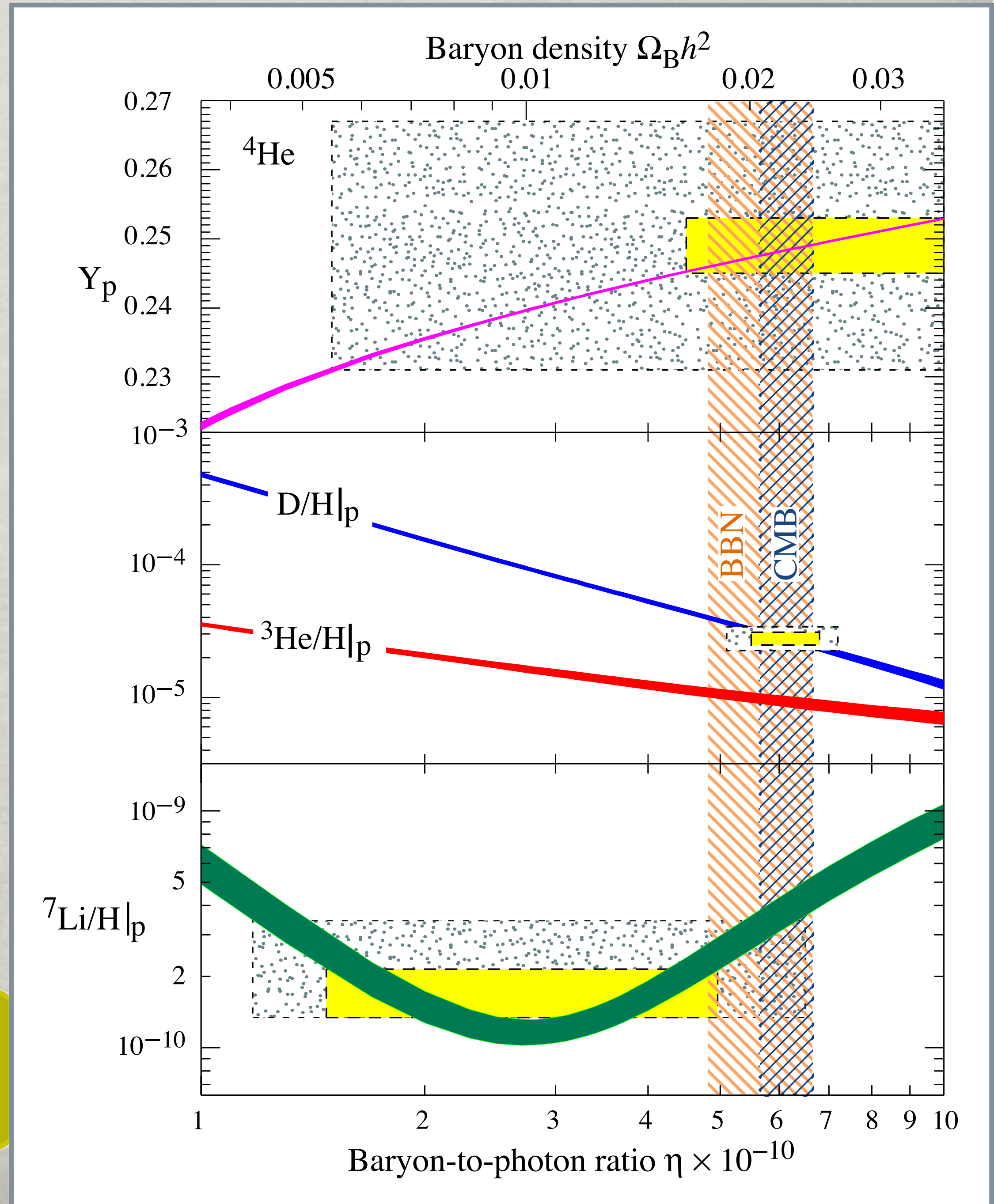


Why $\Omega_{DM} h^2 \sim 5\, \Omega_B h^2$?

Big Bang Nucleosynthesis

[Fields & Sarkar PDG 07]

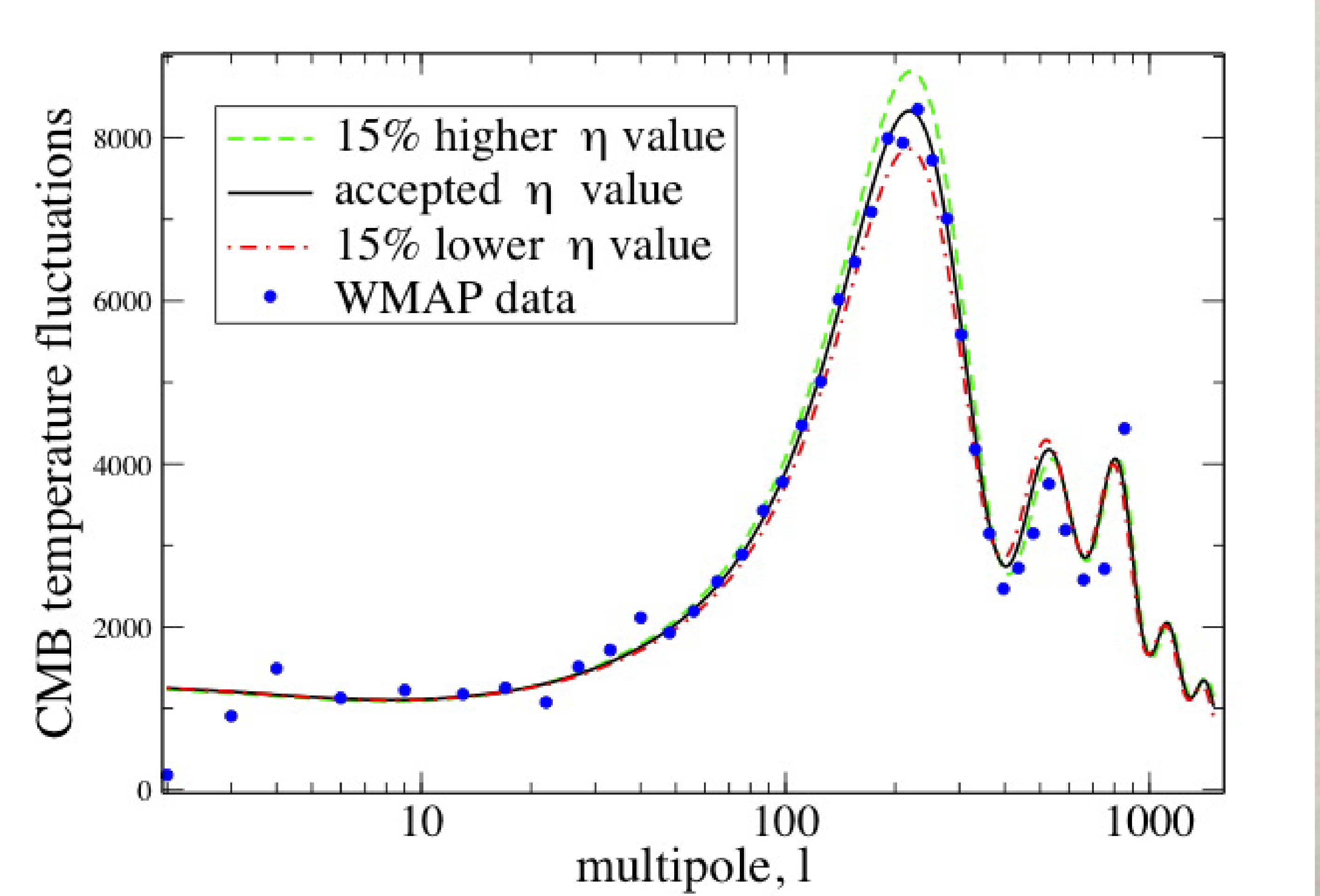
- Light elements abundances obtained as a function of a single parameter $\Omega_B h^2$
- Perfect agreement with WMAP determination
- Some trouble with Lithium 6/7



$$\Omega_B h^2 = 0.02 < \Omega_{DM} h^2$$

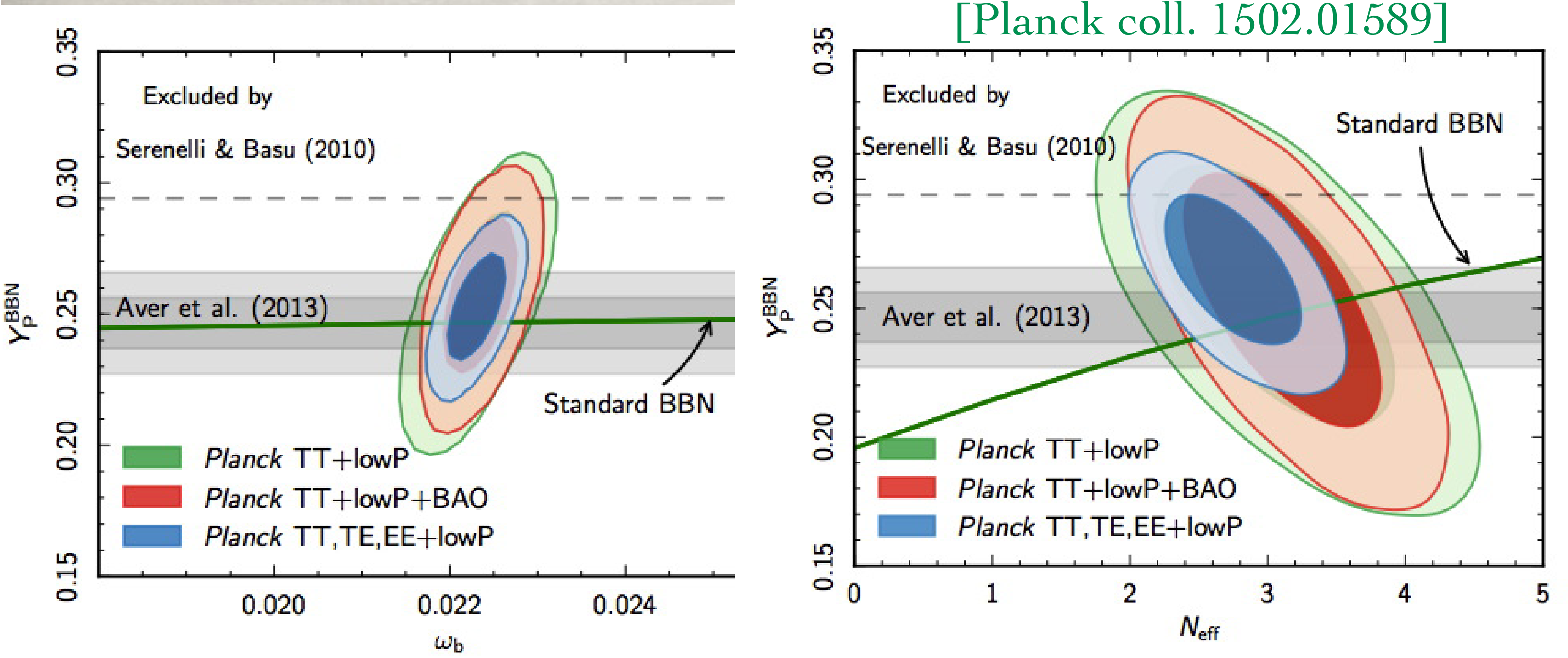
Baryonic Matter evidence

The relative height between the odd (compression) and the even (rarefaction) peaks in the CMB power spectrum depends on the amount of baryons since the mass of the plasma is due to the baryons and DM is decoupled from the photon gas...



Planck:Nucleosynthesis

[Planck coll. 1502.01589]

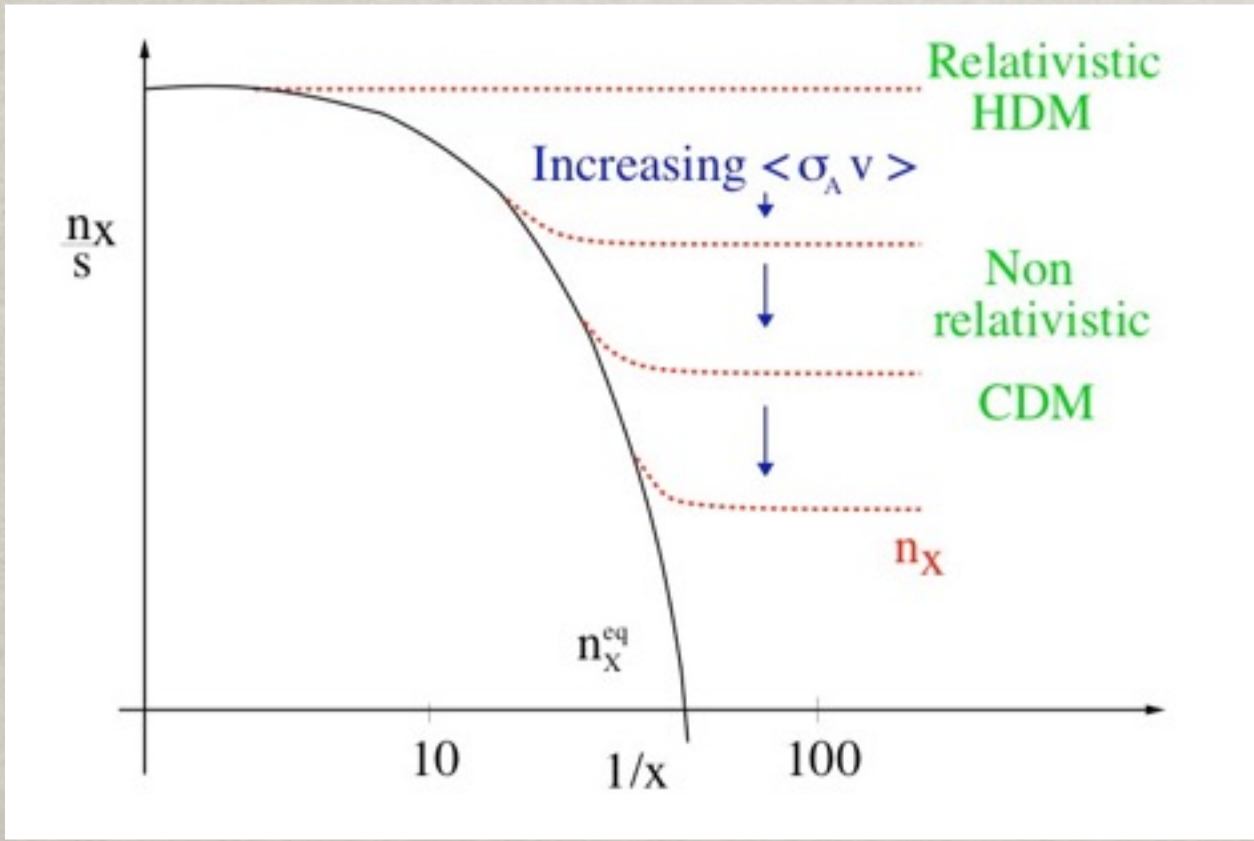


CMB consistent with BBN even fitting both N_{eff} & Y_p .

Note the degeneracy between these two parameters, but orthogonal compared to BBN !

Baryonic Matter

Baryons are in equilibrium and annihilate very strongly so that the symmetric Baryonic component is erased very efficiently to leave only $\Omega_B \sim 10^{-10}$.



Moreover, how to "segregate" it ?

If an asymmetric baryon component is already present, it survives the freeze-out process !

Sakharov Conditions

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

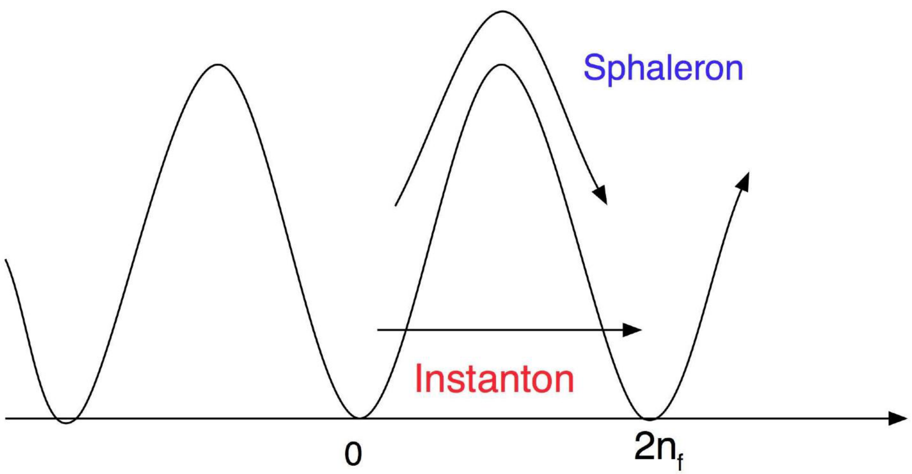
- B violation: trivial condition since otherwise B remains zero...
- C and CP violation: otherwise matter and antimatter would still be annihilated/created at the same rate
- Departure from thermal equilibrium: the maximal entropy state is for B = 0, or for conserved CPT, no B generated without time-arrow...

Now exactly the same conditions have to hold also for the generation of a Dark Matter Asymmetry !

Spheleron Processes

$B + L$ violation in the Standard Model

In the SM the global $U(1)_{B+L}$ is anomalous. This is related to the complex vacuum structure of the theory, which contains vacua with different configurations of the gauge fields and different topological number. Non-perturbative transitions between the vacua change $B + L$ by $2n_f$.



– $T = 0$: tunneling and is suppressed by $e^{-\frac{4\pi}{\alpha_W}} \ll 1$

$\rightarrow B$ & L practically conserved!

– $T > 0$: the transition can happen via a sphaleron

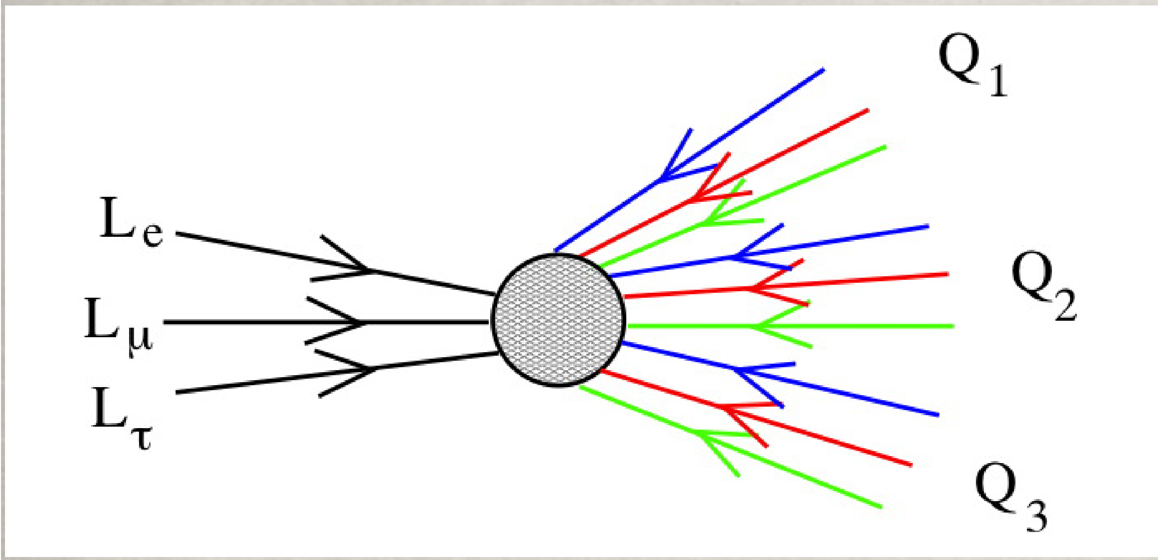
with rate $\Gamma_{sph}(T) \sim \left(\frac{M_W}{\alpha_W T}\right)^3 M_W^4 e^{-E_{sph}/T}$

So at temperatures $T \geq 100$ GeV sphaleronic transitions are in equilibrium in the Universe $\rightarrow B + L$ erased if $B - L = 0$, otherwise

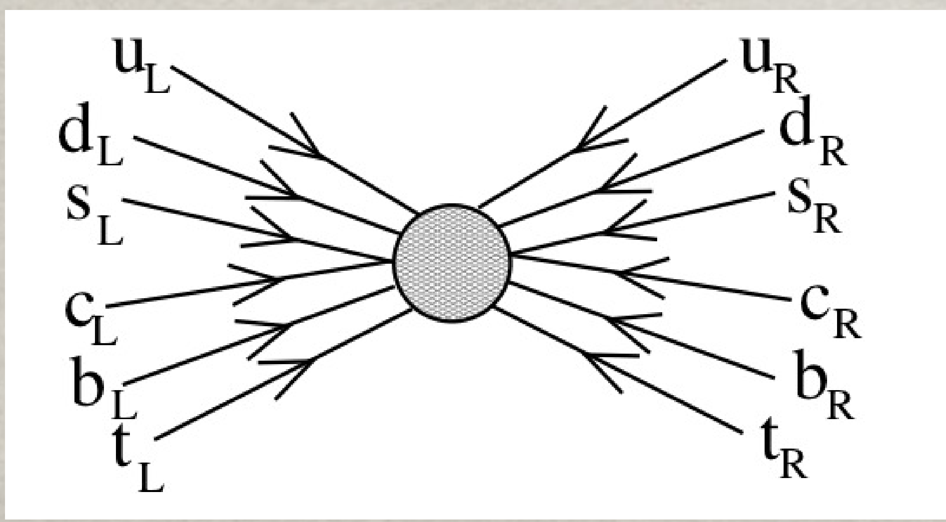
$$B = \frac{8n_f + 4n_H}{22n_f + 13n_H}(B - L)$$

A $B - L$ number is reprocessed into B number !

Spheleron Processes



EW Sphaleron:
B and L both change by -3 units, for n=1 change in Chern-Simons (winding) number, while B-L is conserved



QCD Sphaleron:
chirality charge Q_5 changes by $2n_f$ units

Sakharov Conditions II

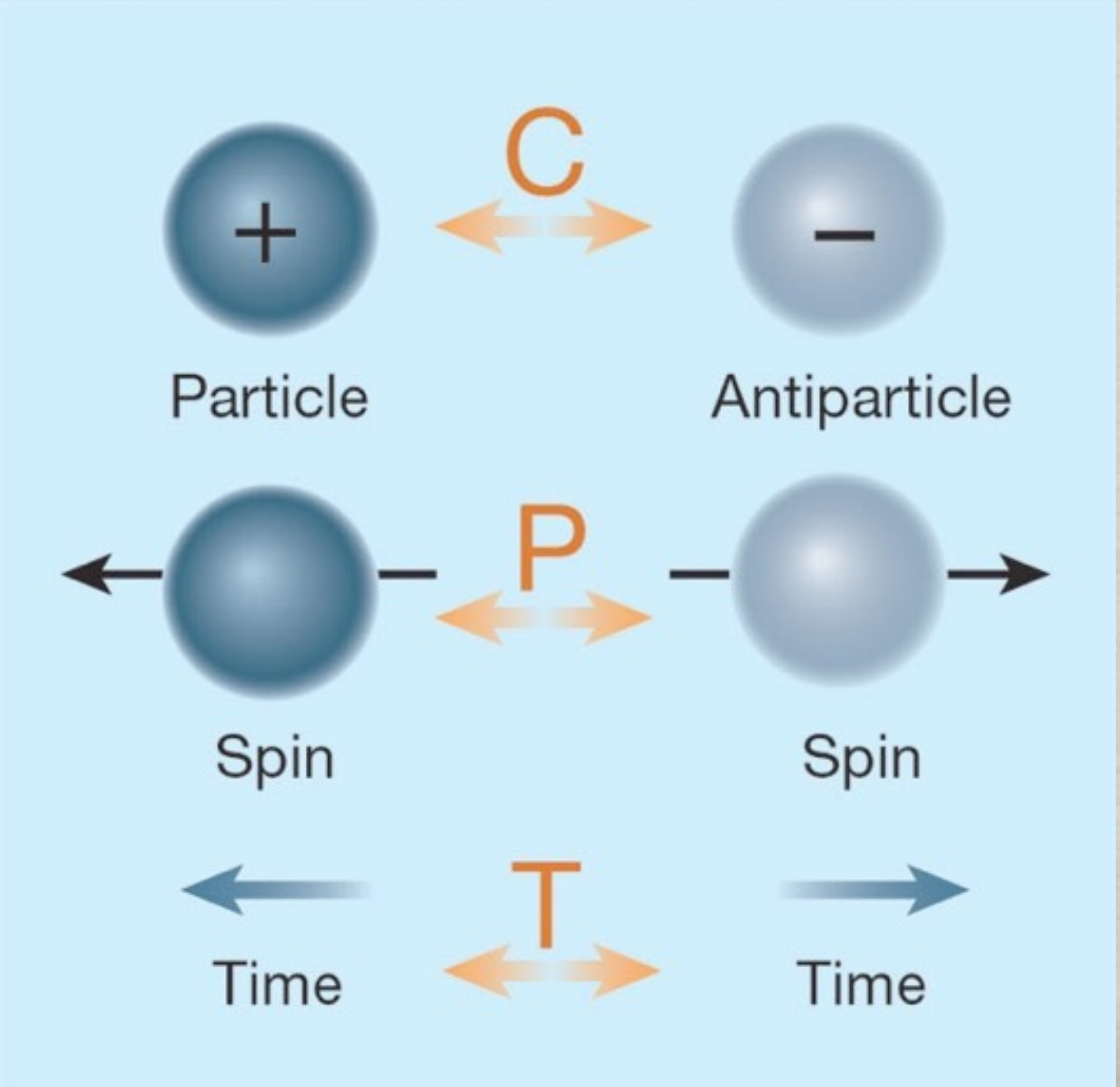
For the Standard Model actually we have instead:

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

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

- 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 ?

C, P, & T symmetries



CPT THEOREM

A Lorentz-invariant QFT with an hermitian Hamiltonian cannot violate the CPT symmetry !

[Lueders & Pauli 1954]

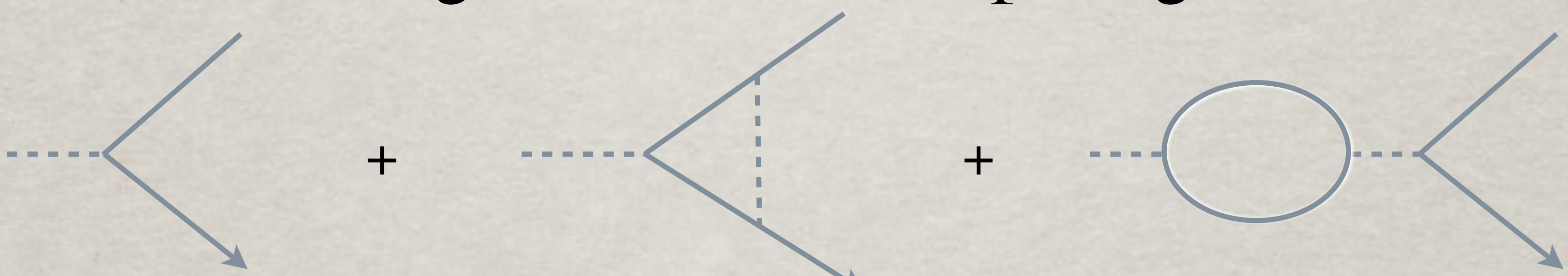
CP violation ⟷ T violation

Consequence of CPT theorem and locality:
particle and antiparticle have the same mass !

But not the same decay rates or scattering rates in the full quantum theory...

CP violation is quantum

At one loop level first signs of CP violation can appear, the most dominant usually the interference effect between tree-diagram and one-loop-diagrams



$$i\,\lambda \qquad i\,\lambda\; i\,\lambda^* i\,\lambda \qquad i\,\lambda\;\; i\,\lambda^*\, i\,\lambda$$

So we have for particle $\mathcal{M} \propto |\lambda|^2 + 2Re\left[\lambda\lambda^*\lambda\lambda^*\ L(x)\right] + \ldots$

& antiparticle: $\overline{\mathcal{M}} \propto |\lambda^*|^2 + 2Re\left[\lambda^*\lambda\lambda^*\lambda\ L(x)\right] + \ldots$

$$\Delta\mathcal{M} \propto 2Re\left[\lambda\lambda^*\lambda\lambda^*\ L(x) - \lambda^*\lambda\lambda^*\lambda\ L(x)\right] + \ldots$$

$$\Delta\mathcal{M} \propto -4\, Im\left[\lambda\lambda^*\lambda\lambda^*\right] Im[L(x)] + \ldots$$

NB: Vanishing for a single coupling, need flavour dependence !

Unitarity relation

We can obtain the same result and the interpretation of the imaginary part of a loop function from the unitarity relation for the scattering matrix & CPT: $S = I - i\,T$

From unitarity: $S^\dagger S = I = I - i(T - T^\dagger) + T^\dagger T$

$$\longrightarrow \quad T = T^\dagger - i\,T^\dagger T$$

Therefore if we square the amplitude we get

$$|T_{fi}|^2 = |T^*_{if}|^2 + 2Im\left[(T^\dagger T)_{fi} T_{if}\right] + |(T^\dagger T)_{fi}|^2$$

From CPT we obtain $T_{if} = T_{\bar{f}\bar{i}}$ and so

$$|T_{fi}|^2 - |T_{\bar{f}\bar{i}}|^2 = 2Im\left[(T^\dagger T)_{fi} T_{if}\right] + |(T^\dagger T)_{fi}|^2$$

CP violation is SMALL

CP violation in particle physics arises as a quantum effect from the interference of tree-level and loop diagrams. For these reasons it is multiply suppressed:

- It is higher order in the couplings, e.g.

  $\Delta\mathcal{M} \propto |\lambda|^4$ compared to $\mathcal{M} \propto |\lambda|^2$

- It contains a loop suppression factor

  $$L(x) \propto \frac{1}{4\pi^2} \sim 0.025$$

- It often needs a non-trivial flavour structure and it is therefore even more suppressed in presence of small mixing between generations.

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

A minimal model for asymmetric DM, neutrino masses and leptogenesis

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.

$$\Psi \to B + X$$

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

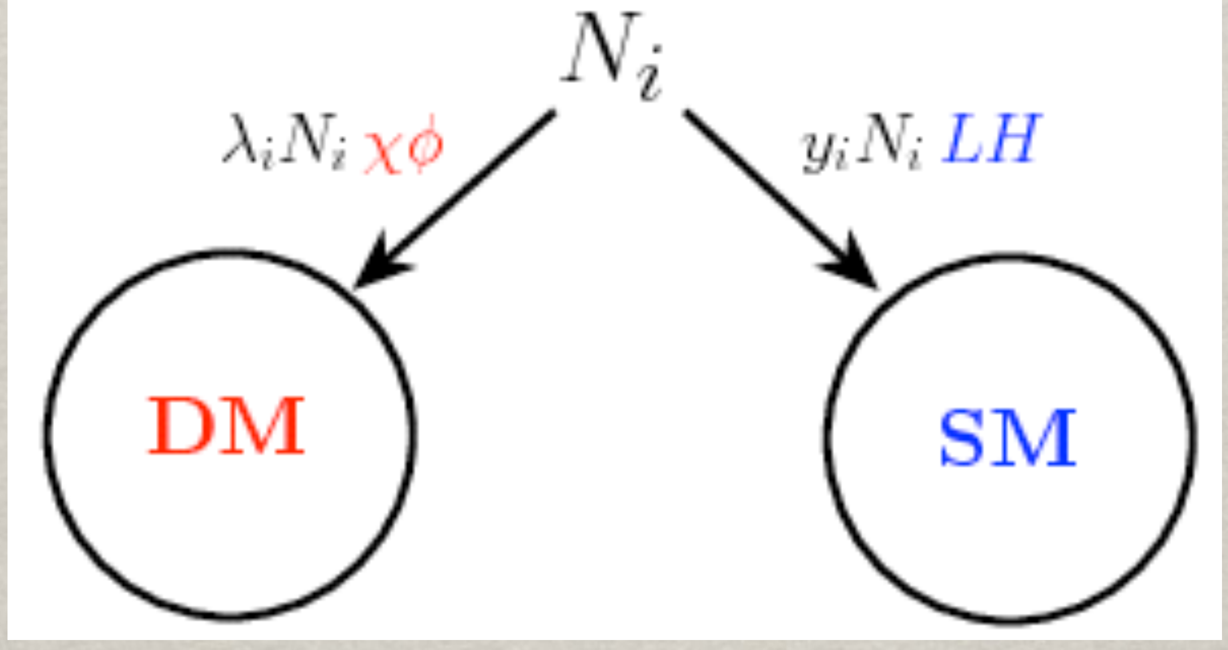
The puzzle of similar densities can be given by similar masses !

Asymmetric Dark Matter

[Griest & Seckel '87, Kaplan, Luty &Zurek 90, …

Falkowski, Rudermann & Volansky 2011]

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



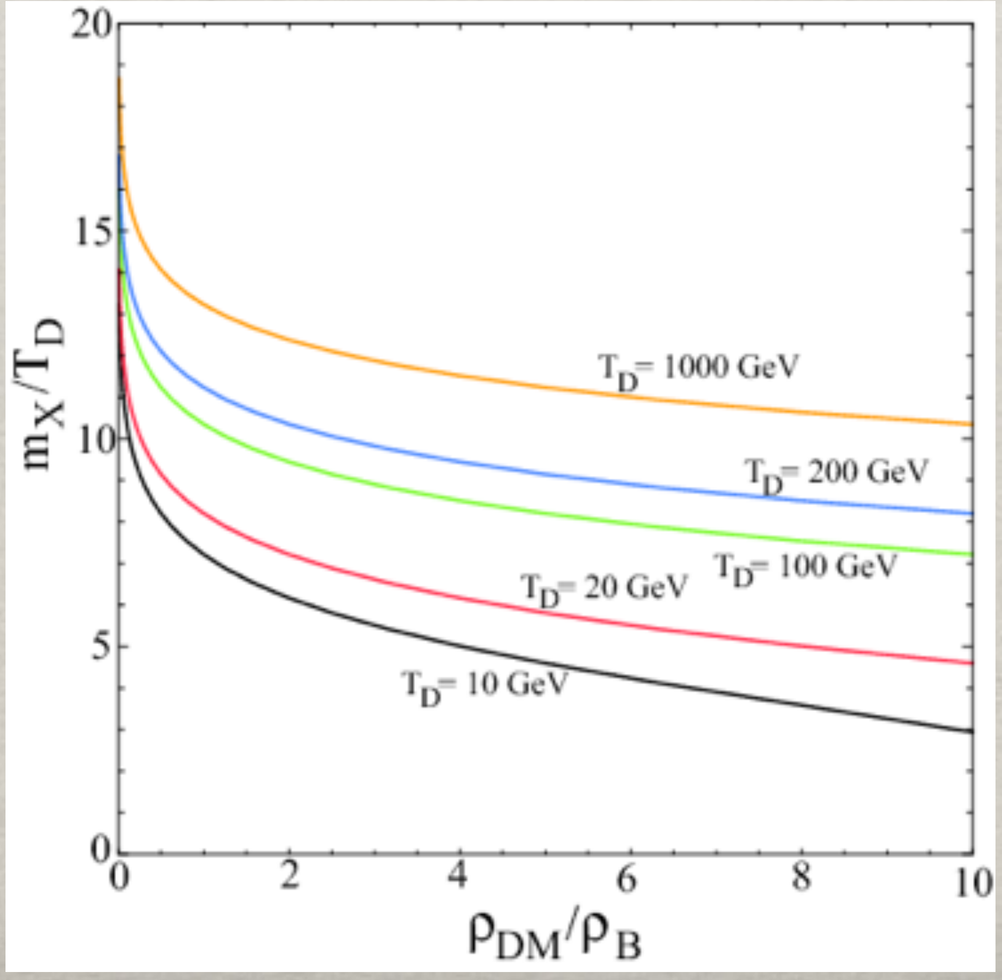
Need similar CP violation in both sectors !

Asymmetric Dark Matter

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

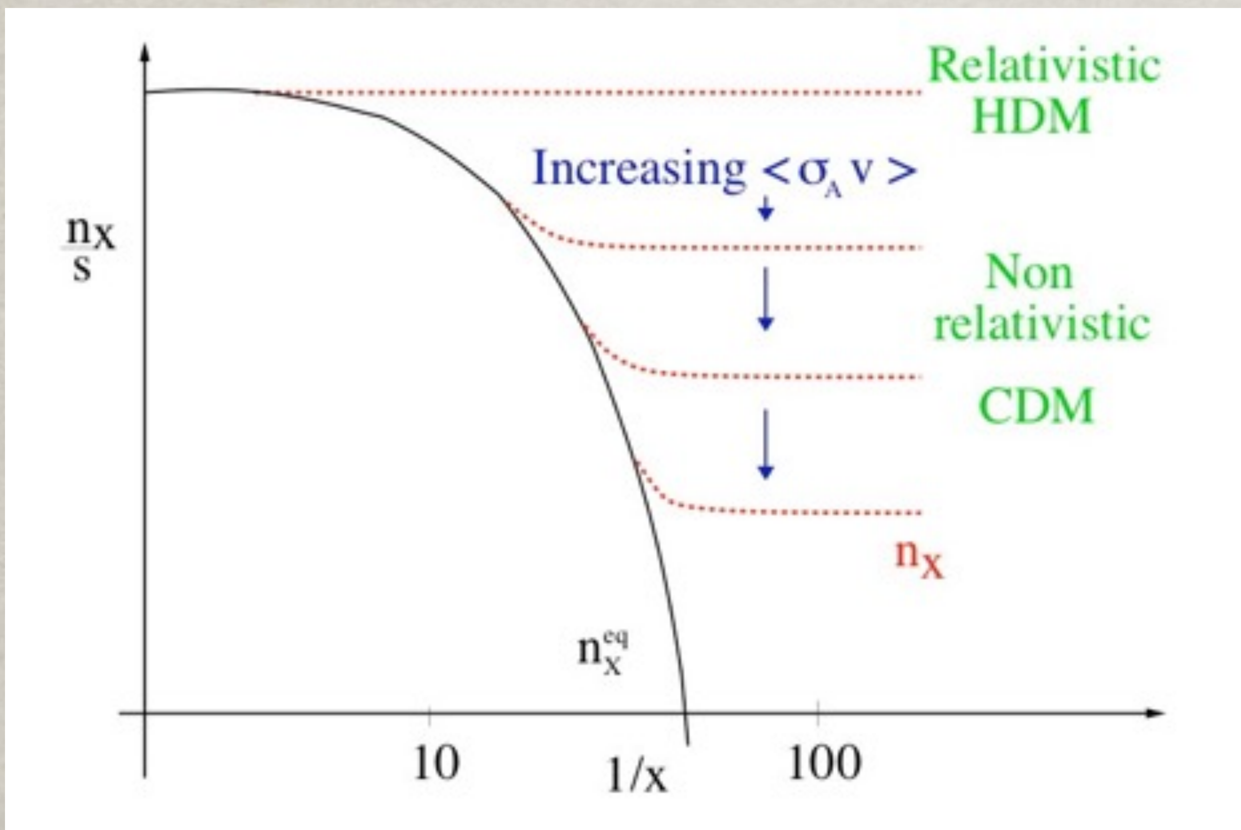
The simple picture $m_{DM} = 5\, m_p$ can be extended by taking into account the Boltzmann suppression factor at the time of creation of the asymmetry:

DM Mass/
T_Decoupling



Asymmetric Dark Matter

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...

A minimal ADM model

[A. Biswas, S. Choubey, LC & S. Khan 2018]

Let us consider a minimal model for leptogenesis with two RH neutrinos to explain the neutrino masses and give the correct mixing matrices, as well as leptogenesis.
The particle content of the model is given by

Gauge Group	Fermion Fields							Scalar Fields		
	$\Psi_{1L} = (\psi_1, \psi_2)_L^T$	ψ_{1R}	ψ_{2R}	$\Psi_{2L} = (\psi_3, \psi_4)_L^T$	ψ_{3R}	ψ_{4R}	N_i	ϕ_h	ϕ_D	η_D
$SU(3)_c$	1	1	1	1	1	1	1	1	1	1
$SU(2)_L$	1	1	1	1	1	1	1	2	1	1
$SU(2)_D$	2	1	1	2	1	1	1	1	2	2
$\mathbb{Z}_3 \times \mathbb{Z}_2$	$(\omega, 1)$	$(\omega, 1)$	$(\omega, 1)$	$(\omega^2, -1)$	$(\omega^2, -1)$	$(\omega^2, -1)$	$(1, 1)$	$(1, 1)$	$(1, 1)$	$(\omega, 1)$

We need an additional Dark SU(2) in order to annihilate away the symmetric DM component and a discrete symmetry to reduce the number of possible couplings.

A minimal ADM model

[A. Biswas, S. Choubey, LC & S. Khan 2018]

The neutrino masses and mixings can be accommodated with just two RH neutrinos, the 2x3 Dirac mass matrix is:

$$M_D = \frac{y_{ij}\, v}{\sqrt{2}} = \frac{v}{\sqrt{2}} \begin{pmatrix} y_{ee} & y^R_{e\mu} + i y^I_{e\mu} \\ y_{\mu e} & y^R_{\mu\mu} + i y^I_{\mu\mu} \\ y_{\tau e} & y^R_{\tau\mu} + i y^I_{\tau\mu} \end{pmatrix}$$

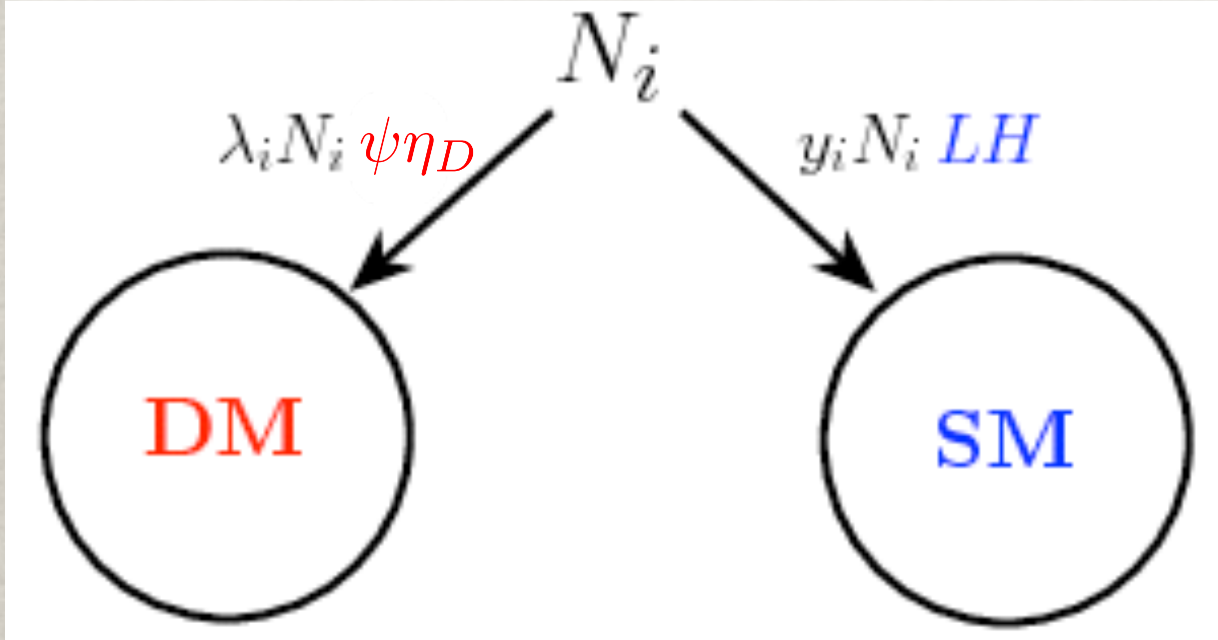
For the case of a pure imaginary second column we have:

$$(m_\nu)_{ij} = -\frac{v^2}{2M_1} y_{ie} y_{je} + \frac{v^2}{2M_2} y^I_{i\mu} y^I_{j\mu}$$

Real neutrino matrix in this limit ! Mass eigenvalues with opposite sign → the Majorana phase is maximal !

Asymmetric Dark Matter

The decay of the lightest RH neutrino generates at the same time an asymmetry in leptons and DM:

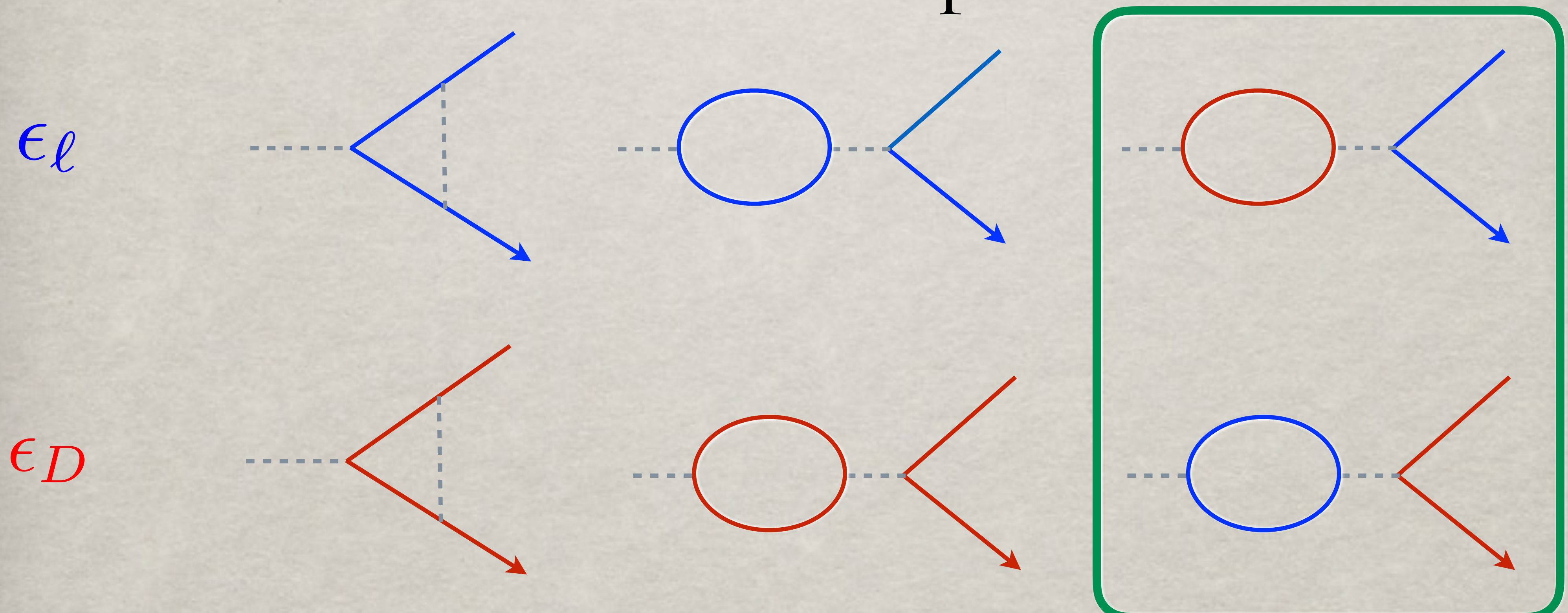


Need similar CP violation in both sectors !

CP violation for ADM

[A. Biswas, S. Choubey, LC & S. Khan 2018]

The CP asymmetry in the decay has generally contributions from both lepton/DM sectors:



But the wave-function contribution with virtual leptons/DM can dominate both asymmetries and give $\epsilon_\ell = \epsilon_D$!

CP violation for ADM

[A. Biswas, S. Choubey, LC & S. Khan 2018]

The CP asymmetry in both decays comes from the same phases, contained in the neutrino sector, since the DM couplings can be chosen real:

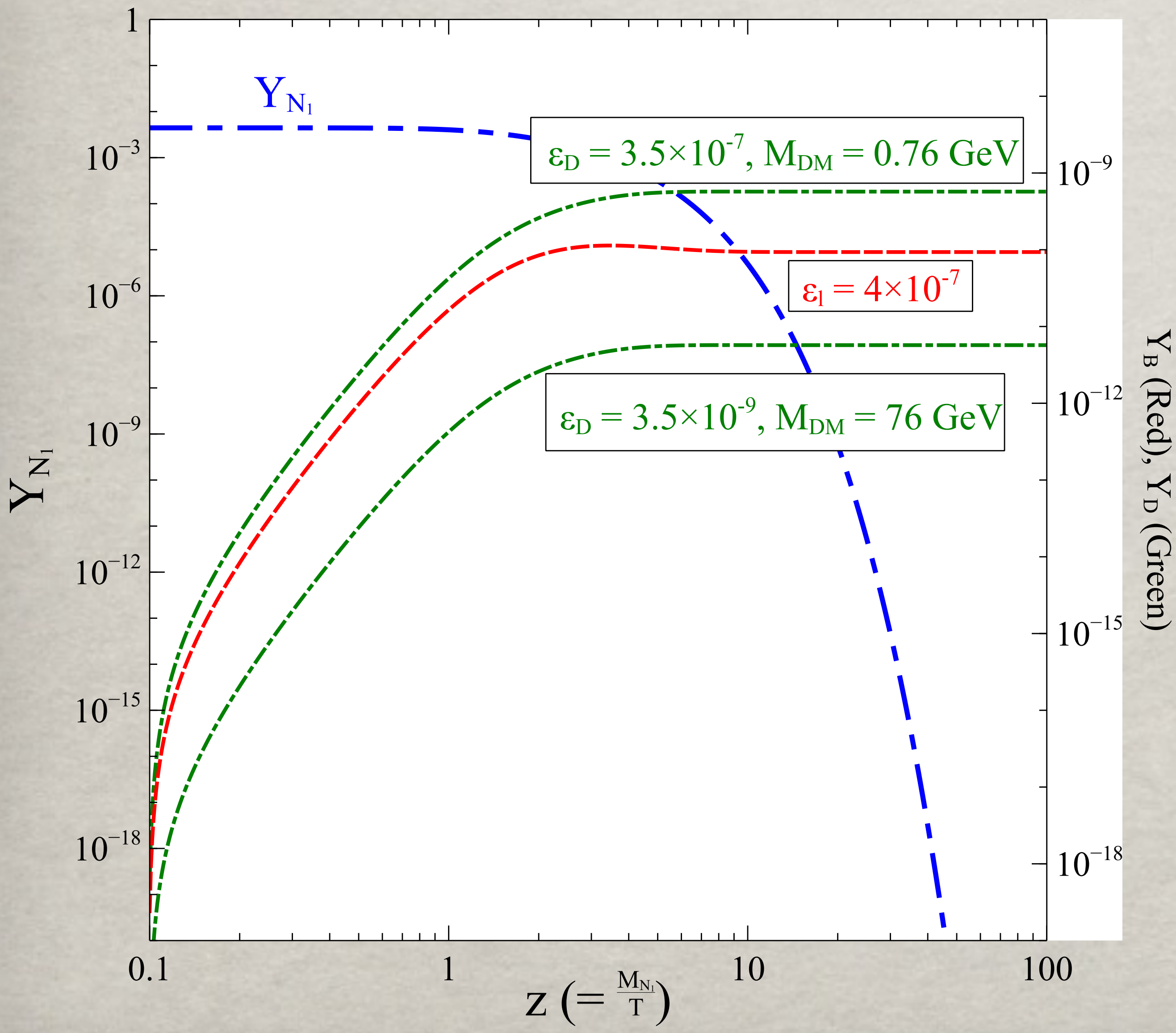
$$\frac{\epsilon_\ell}{\epsilon_D} = 1 + \frac{\mathrm{Im}\left[3((\mathrm{y}^\dagger \mathrm{y})^*_{12})^2\right]}{2\alpha_1\alpha_2 \mathrm{Im}\left[3(\mathrm{y}^\dagger \mathrm{y})^*_{12}\right]}$$

For one real and one imaginary columns of Yukawas, then we have Real $((y^\dagger y)^*_{12})^2$ and exactly $\epsilon_\ell = \epsilon_D$.

Similarly in case of $\alpha_1\alpha_2 > |(y^\dagger y)_{12}*|$ we also obtain practically equal CP violation in the decays.

A minimal ADM model

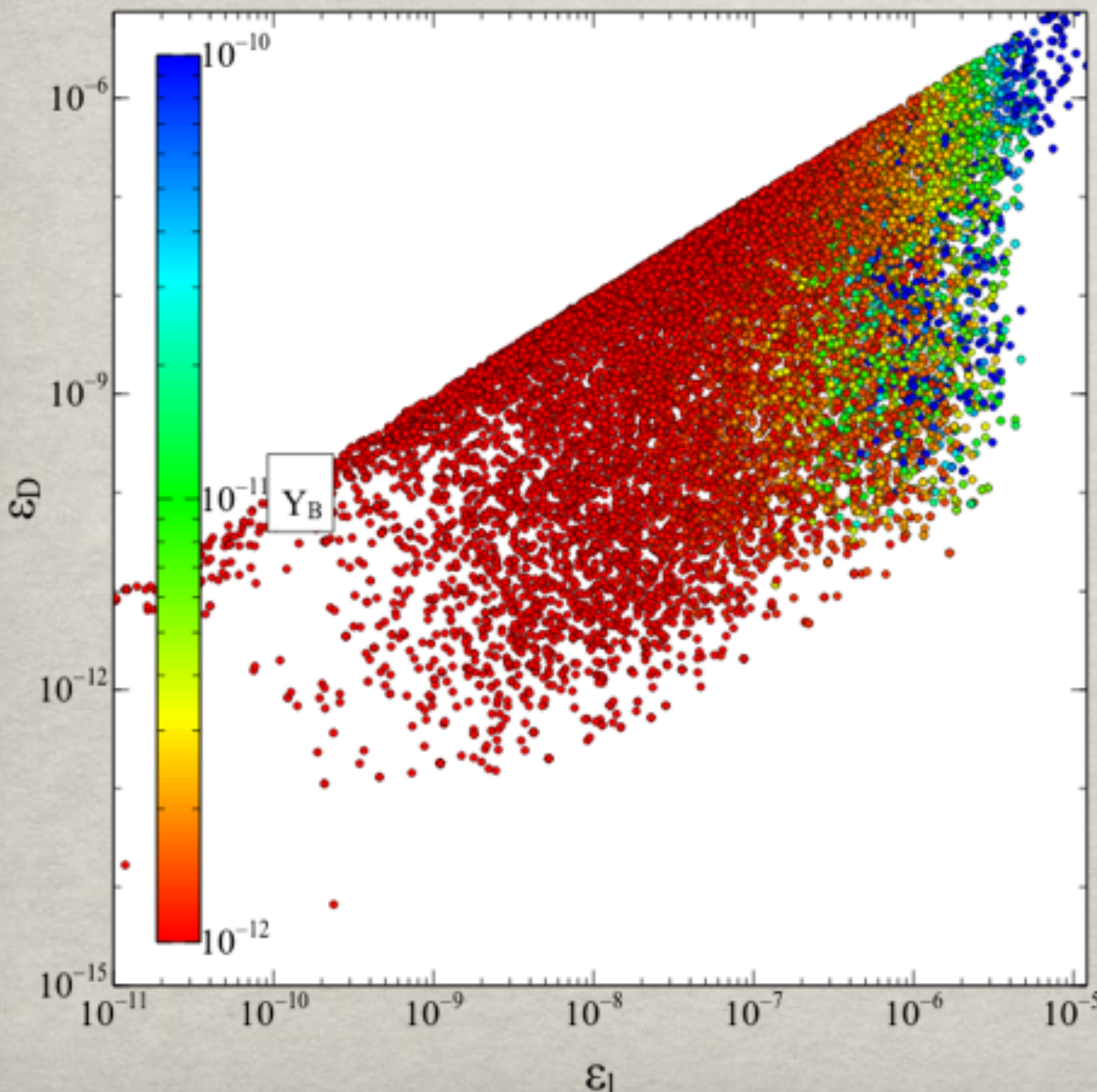
[A. Biswas, S. Choubey, LC & S. Khan 2018]



Even if the CP parameter
is the same, also wash-out processes play a role and naturally give a larger asymmetry in the DM sector than in the lepton sector !

A minimal ADM model

[A. Biswas, S. Choubey, LC & S. Khan 2018]

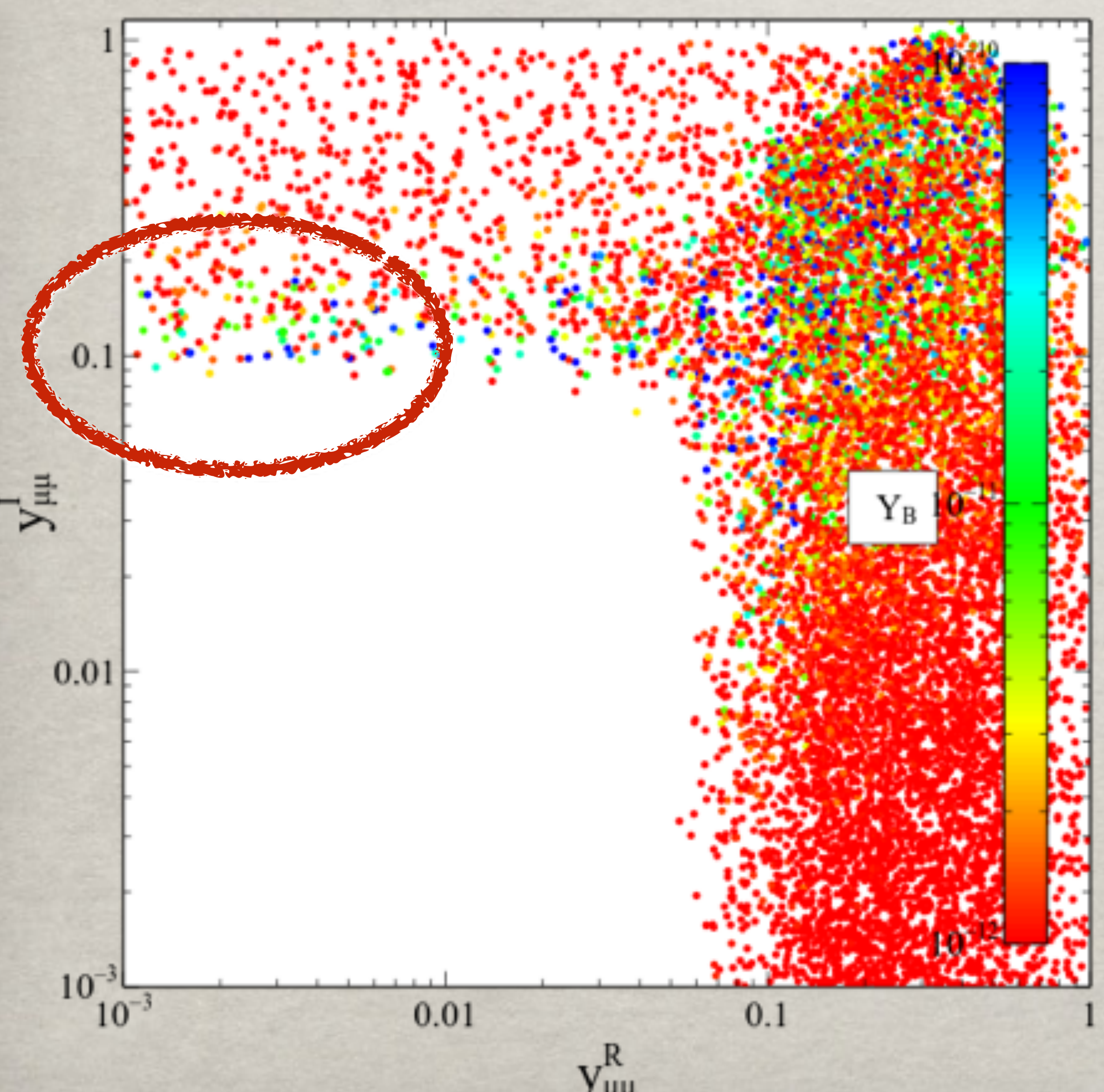


Generically need largish ϵ_ℓ in order to obtain the full baryon asymmetry.

For the Dark Sector, also smaller values are OK if we tune the DM mass to compensate.

A minimal ADM model

[A. Biswas, S. Choubey, LC & S. Khan 2018]



For the Yukawa couplings of the neutrino sector, this means that the imaginary part of the couplings have to be large !

Indeed also pure imaginary coupling can satisfy all (apart $\delta_{CP} = 215^{\circ}(NH)/284^{\circ}(IH)$) !

Neutrinoless $\beta\beta$ decay

As in any model with only two RH neutrinos, one light neutrino mass eigenvalue vanishes and no full cancellation can happen in the effective mass:

$$m_{eff} = \left|\sum_i m_i U_{ei}^2\right| \quad \text{gives} \qquad 1,5 \text{ meV} \leq m_{eff} \leq 3,7 \text{ meV}$$

for the case of normal hierarchy as

$$m_{eff}^2 = m_3^2 \sin^4\theta_{13} + m_2^2 \cos^4\theta_{13} \sin^4\theta_{12} + 2m_3 m_2 \sin^2\theta_{13} \cos^2\theta_{13} \sin^2\theta_{12} \cos(2\alpha + 2\delta_{CP})$$

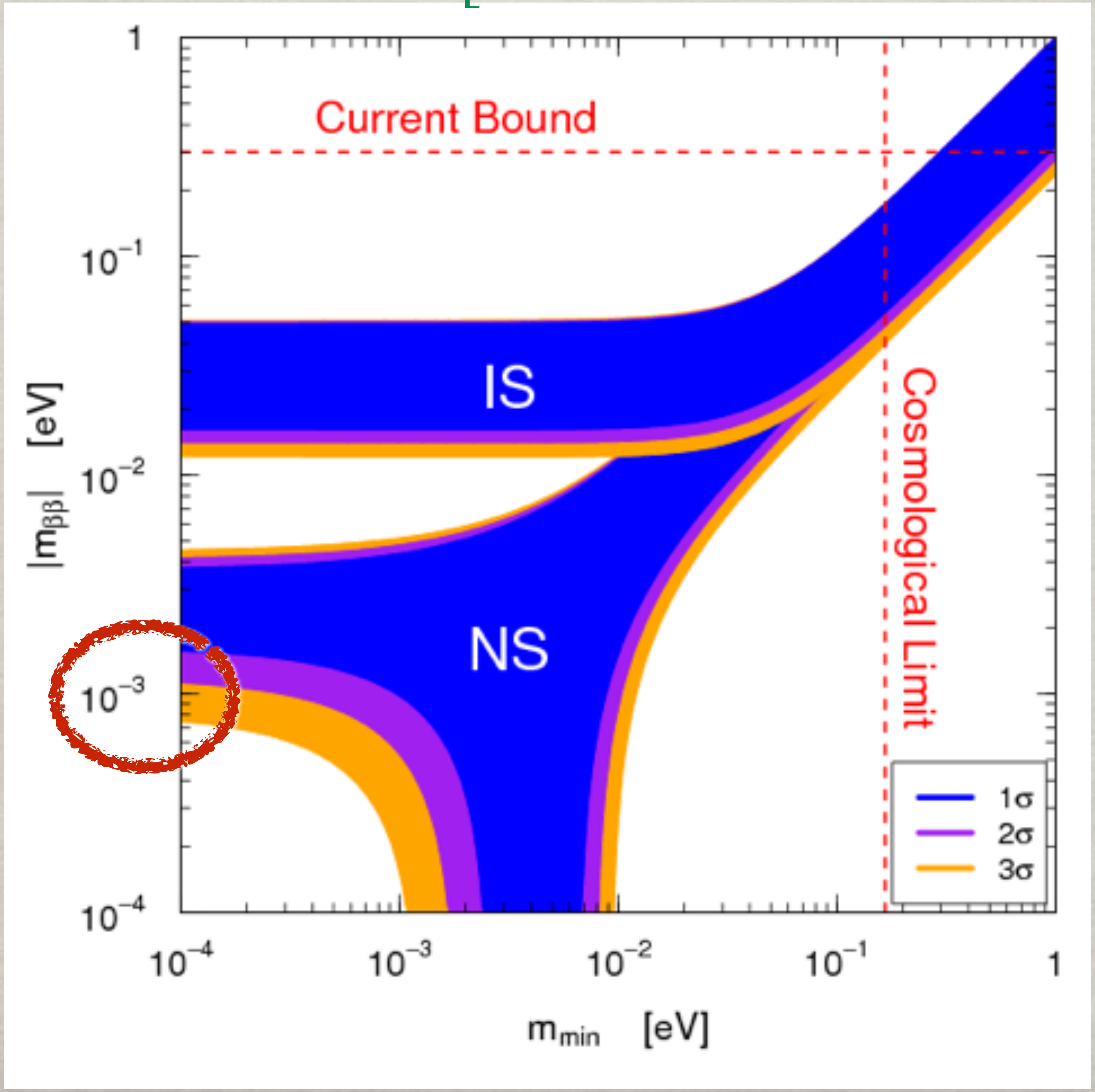
Minimal case of imaginary second column with $\delta_{CP} = 0, \alpha = \pi/2$

$$m_{eff} = |m_2 \cos^2\theta_{13} \sin^2\theta_{12} - m_3 \sin^2\theta_{13}|$$

Minimal value for zero eigenvalue !

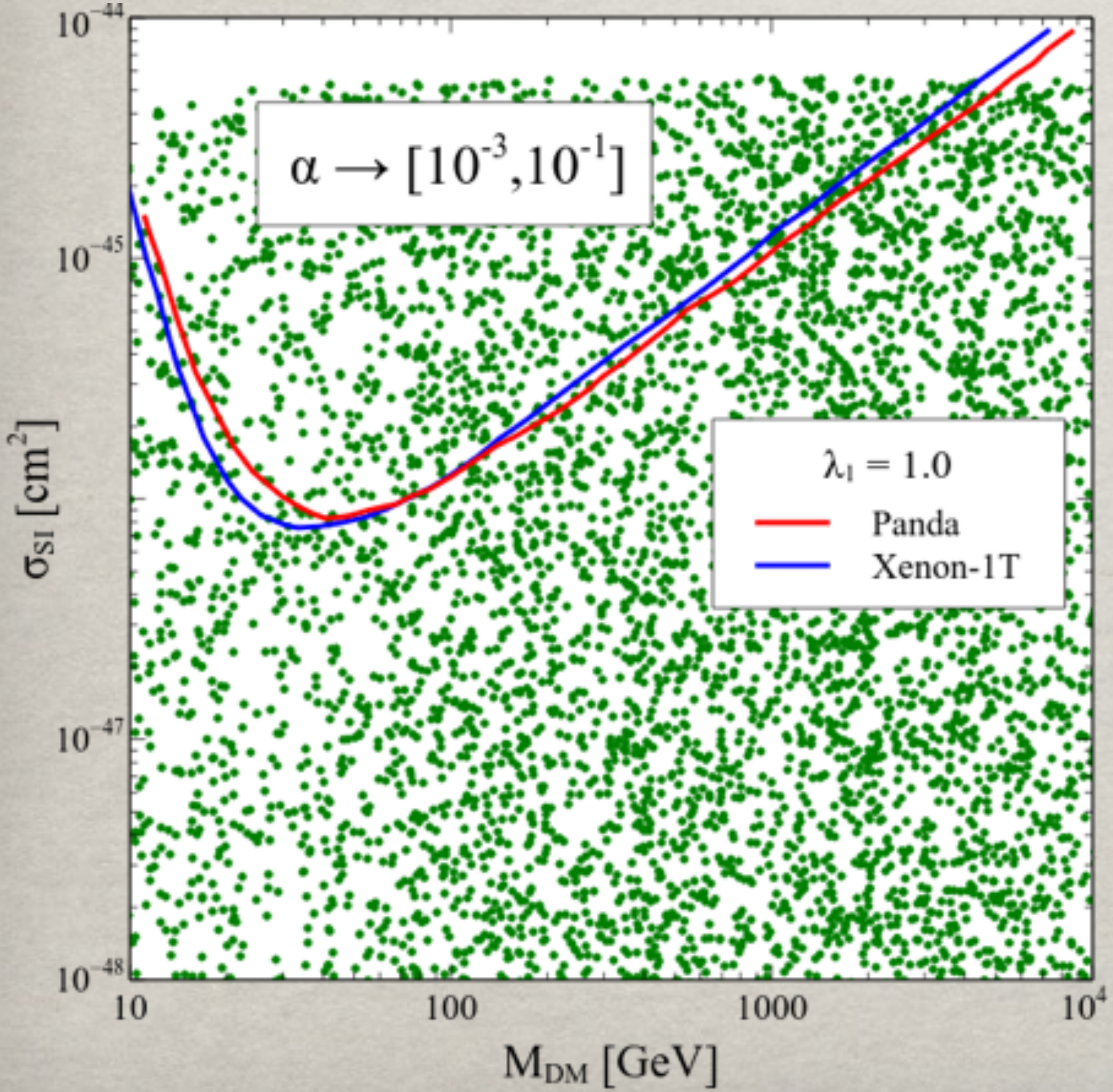
Neutrinoless $\beta\beta$ decay

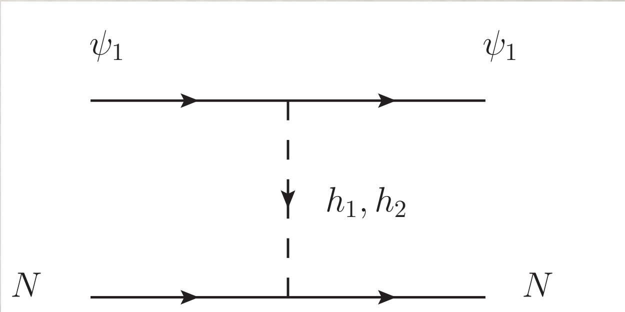
[S. Bilenki and C. Giunti 2012]



DD in the ADM model

[A. Biswas, S. Choubey, LC & S. Khan 2018]



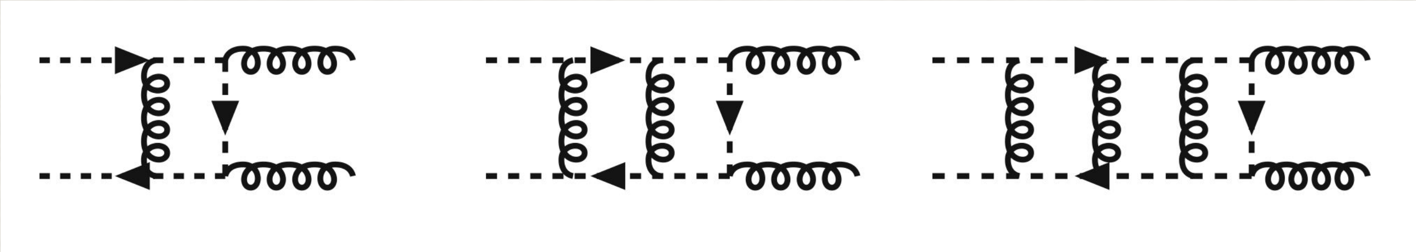


Due to the mixing of the scalars after EW symmetry breaking, the DM scatters with normal matter via intermediate Higgs and could be detected in DD (but beware of the cancellation!)

Sommerfeld enhancement at finite temperature

Sommerfeld Factor

[Sommerfeld 39, Sakharov 48]



- Consider one particle moving in the Coulomb field produced by the other... In Feynman diagrams it correspond to resumming all ladder diagrams with soft/static gauge bosons. The effect arises from the IR/long-range nature of the force !
- The cross-section factorizes for a massless gauge boson:

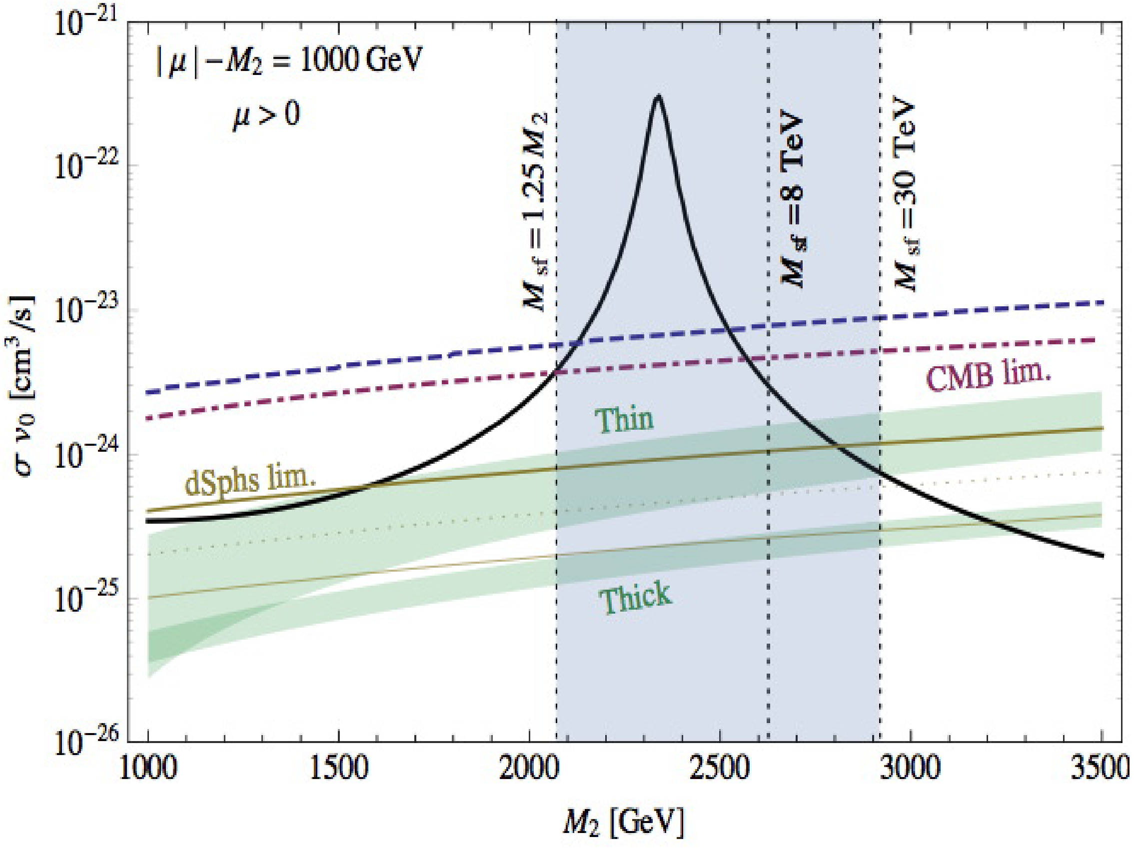
$$\sigma_S = \sigma_0 \times E_S(\beta) \qquad E_S(\beta) = \frac{z}{1 - e^{-z}} \quad \text{with} \quad z = \frac{C\pi\alpha_N}{\beta}$$

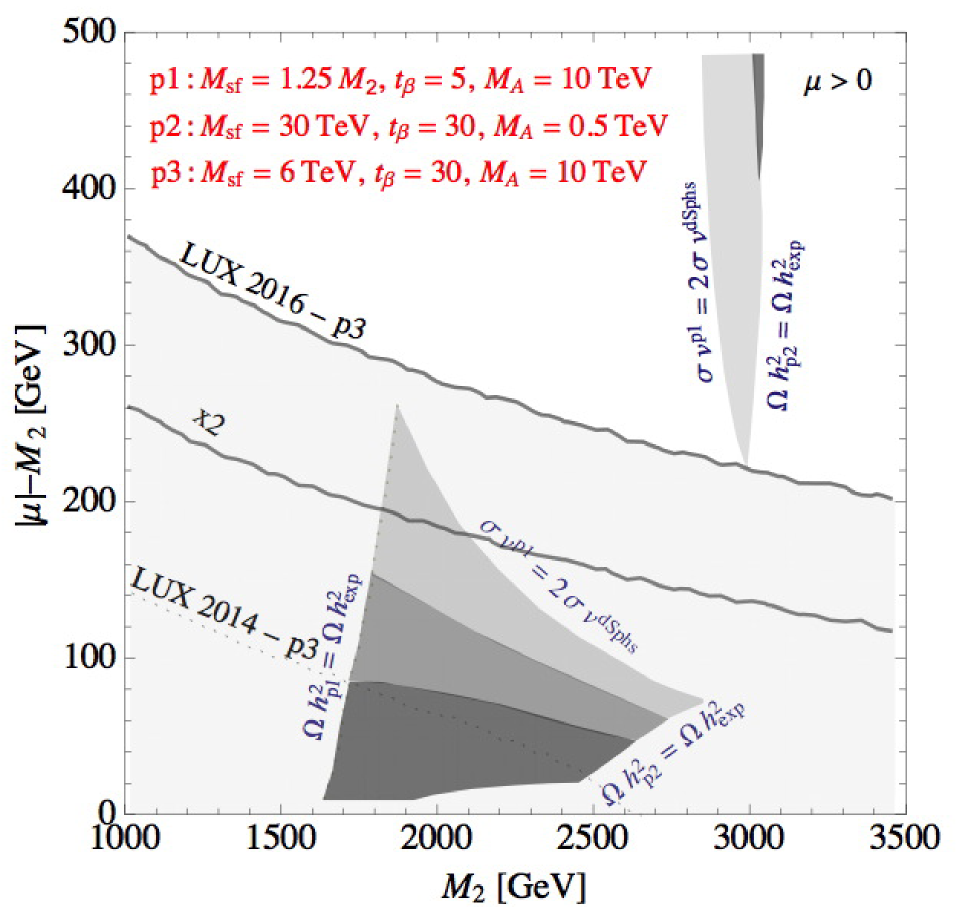
- Dominant correction for small velocity !!!
  RELEVANT AT FREEZE-OUT and TODAY !

Wino Dark Matter

In the case of the Wino the Sommerfeld enhancement of the cross-section plays an important role ! In this case then indirect detection can exclude pure Wino and also most of the Wino-Higgsino parameter space...

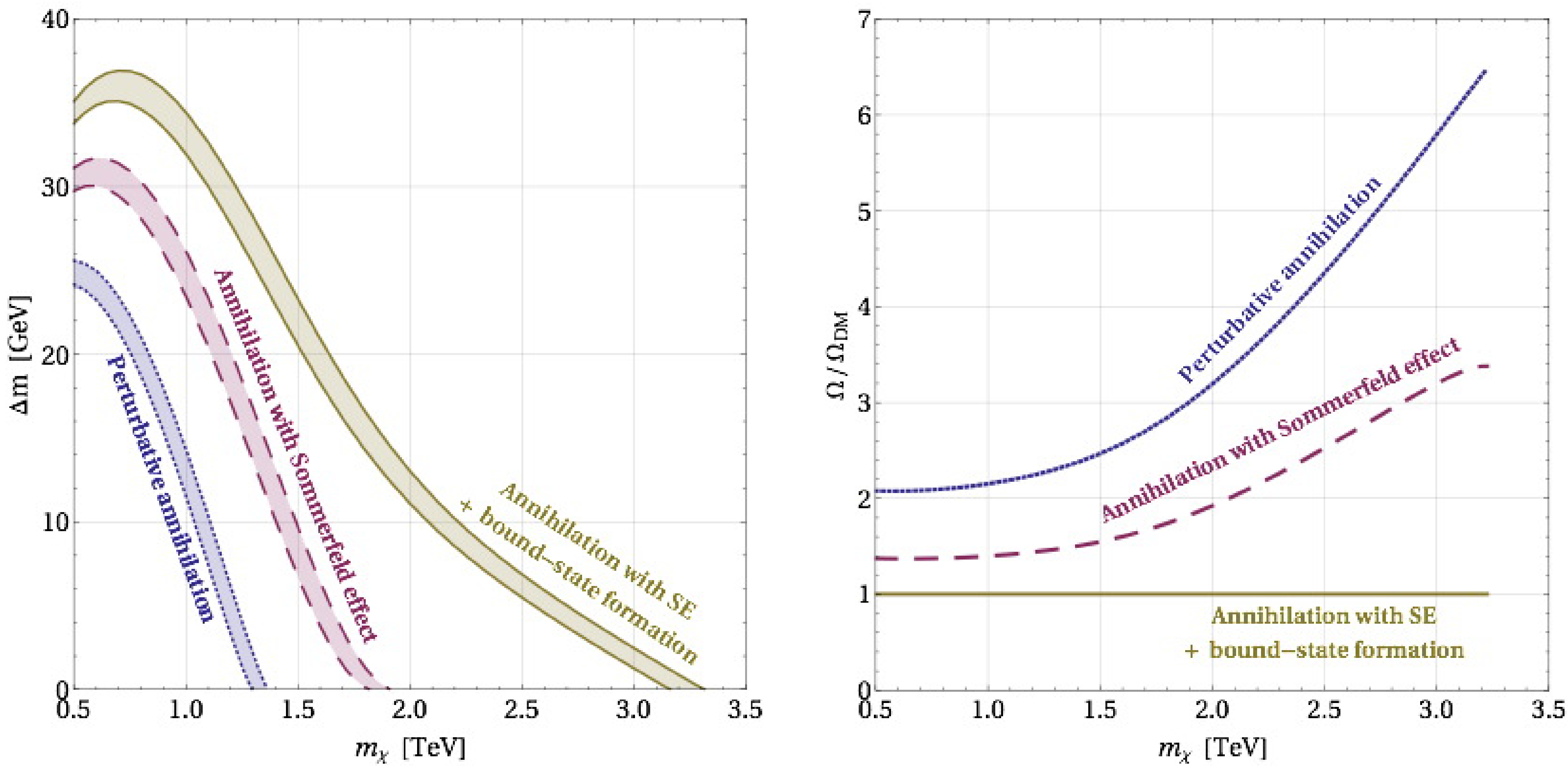
[Beneke et al.1611.00804]





Sommerfeld Factor for coannihilation

[J. Harz & K. Petraki 2018]



Coannihilation with a colored state:bound states are important !

Plasma effects ?

[Berger, LC, Kraml, Palorini 08]

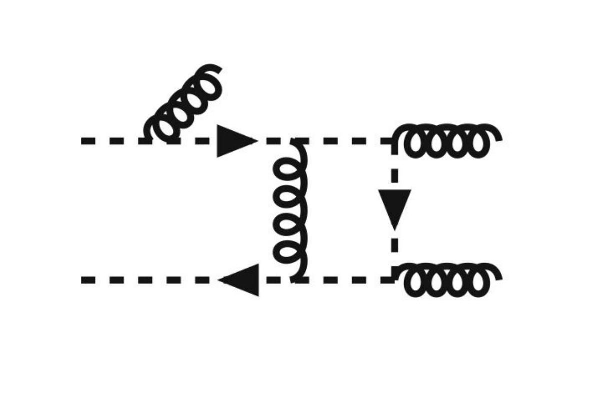
- Plasma screening/Debye thermal mass for the gluon: depends on

$$m_D \sim gT \ll M\beta \sim \sqrt{MT}$$

- Mixing between initial state configurations and loss of coherence:
  the Sommerfeld factor at T=0 depends on the channel, e.g. it is attractive (C>0) for the singlet case, but repulsive (C<0) for the adjoint configuration. In a thermal plasma there is no definite colour configuration....

$$N \times \bar{N} = S + A$$

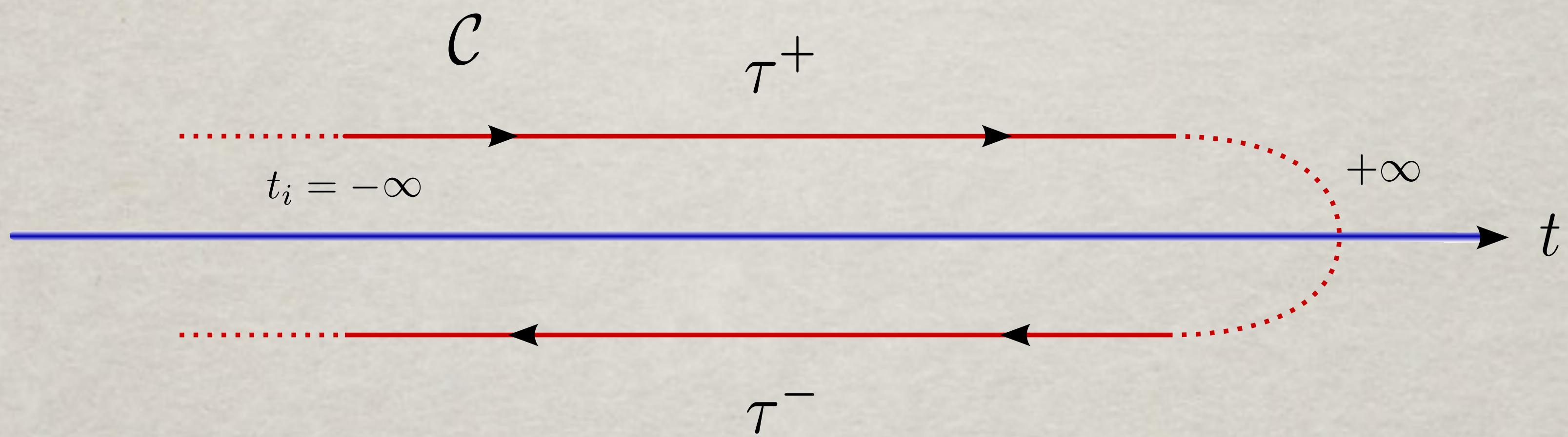
$$S \leftrightarrow A + g$$



How to really treat this?

[T. Binder, LC, K. Mukaida '18]

Start from first principles applying Thermal Field Theory in the real-time formalism on the Keldish contour:



Then the propagator and all the higher point functions become matrices depending on the position of the time variables on the positive/negative time branch:

$$\begin{pmatrix} G^{++}(x,y) & G^{+-}(x,y) \\ G^{-+}(x,y) & G^{--}(x,y) \end{pmatrix}$$

They contain both the T=0 propagator and the statistical propagator.

Non-relativistic limit

In order to simplify the problem, we consider a simple U(1) model with a (light) gauge field and light fermions in the plasma together with a non-relativistic heavy fermion as the Dark Matter. All fermions are charged under the U(1).

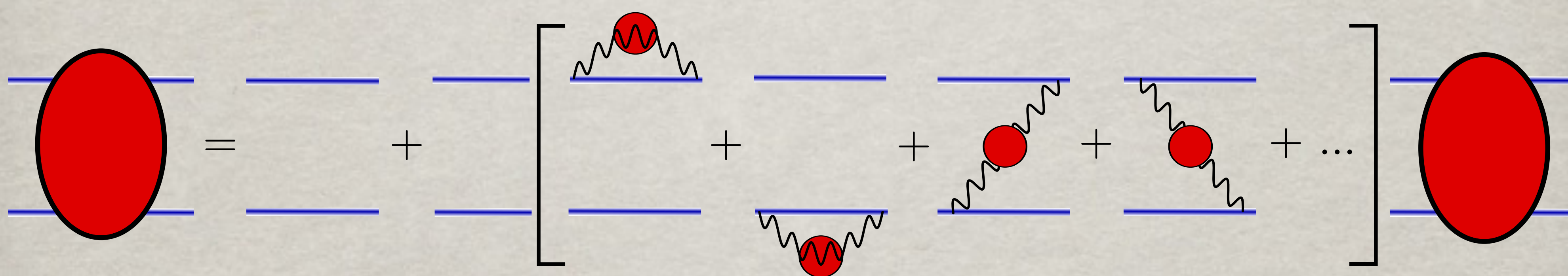
- We can write down the action for the NR Dark Matter and consider the Dyson series for the DM correlation functions;
- We close the hierarchy of equations at the level of the 4 point-function to be able to describe bound and scattering states;
- We consider the HTL resummed gauge boson propagator to include the interaction with the thermal plasma

$$\lim_{E\to 0} G^{++}(E,\vec{p}) = \frac{i}{\vec{p}^{\,2}+m_V^2+m_D^2} + \pi \frac{T}{p}\frac{m_D^2}{(\vec{p}^{\,2}+m_V^2+m_D^2)^2}$$

Bethe Salpeter equation

[T. Binder, LC, K. Mukaida '18]

We define a resummation procedure taking into account the self-energy corrections to the DM propagator and to the gauge boson propagator to obtain an equation that respects thermal equilibrium properties (KMS conditions, etc.):



DM scatterings

Force screening

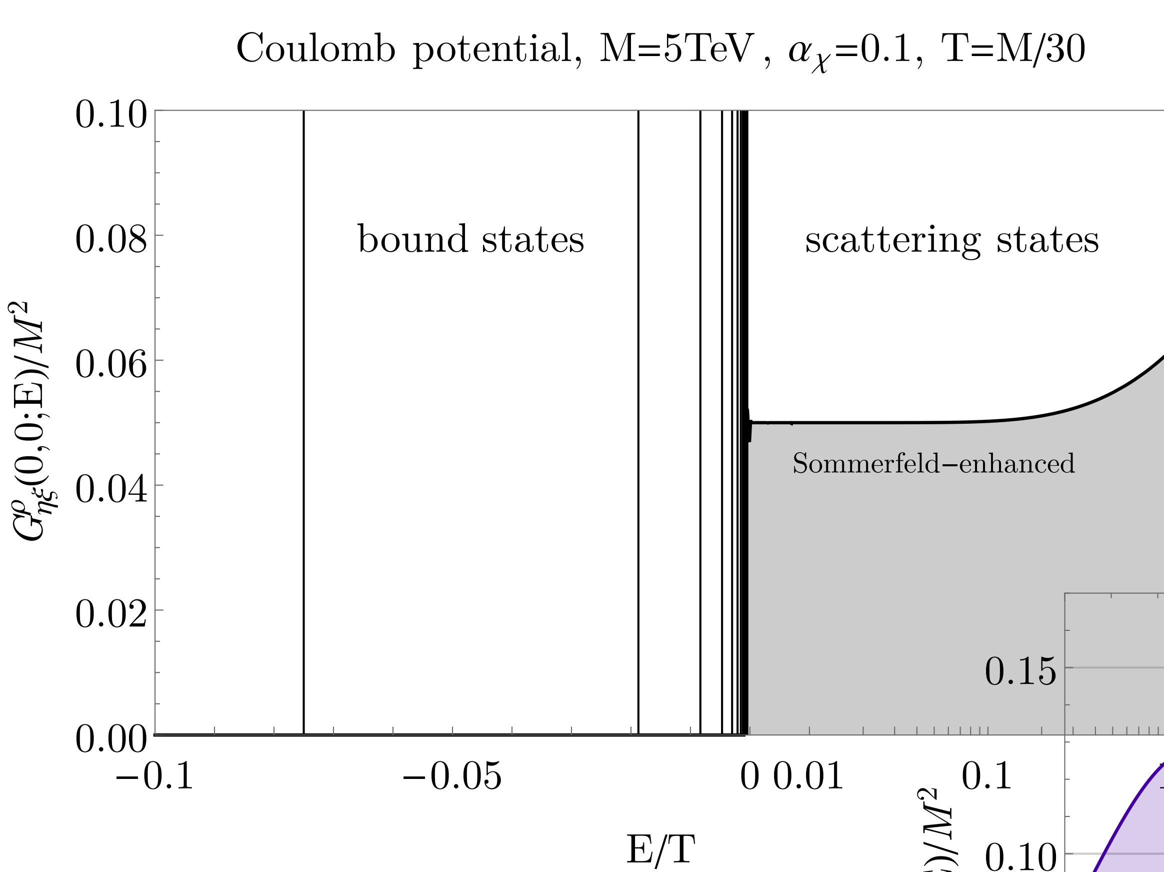
In the DM dilute limit, we obtain from this equation the modified Coulomb potential:

Yukawa-like ! Imaginary

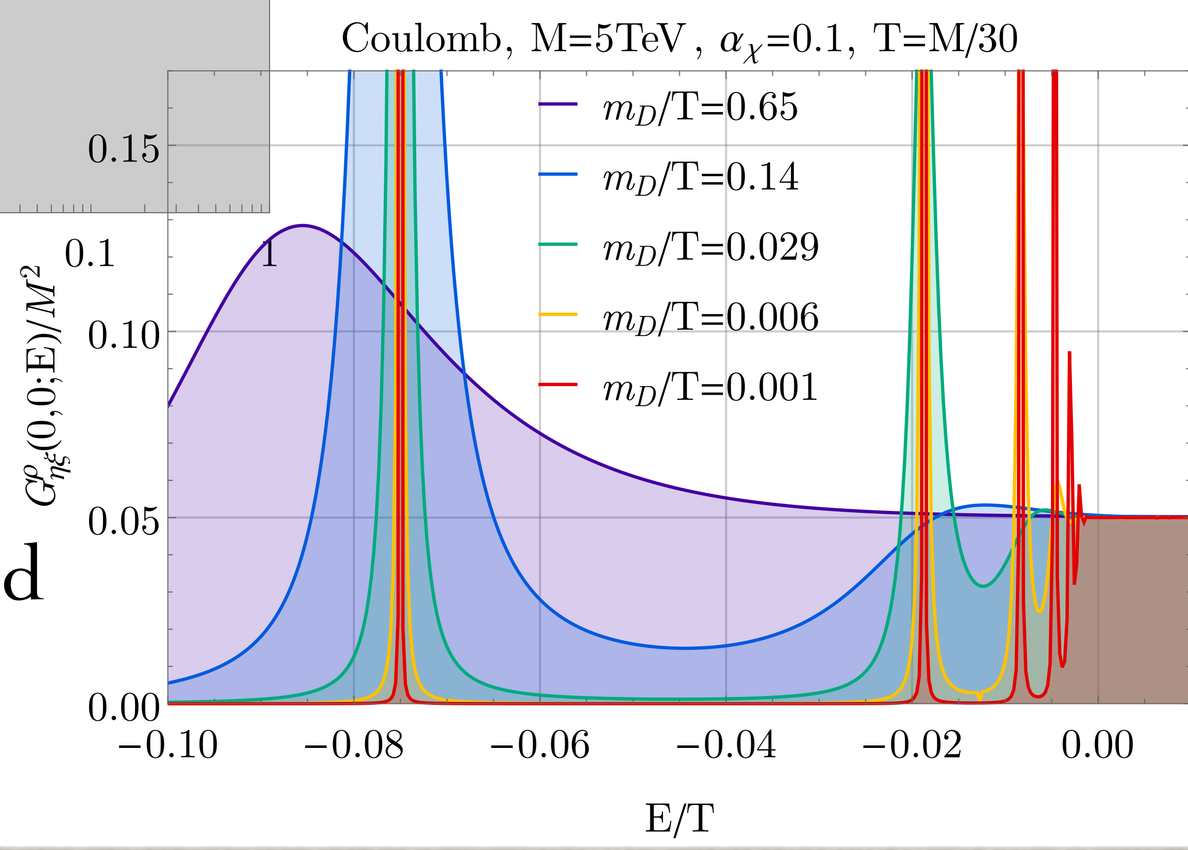
$$V_{eff}(\vec{r}) = -ig^2 \int_{-\infty}^{+\infty} d^3q (1 - e^{i\vec{q}\vec{r}}) G^{++}(0,\vec{q}) = -\frac{\alpha}{r} e^{-m_D r} - i\alpha T \Phi(m_D r) + \ldots$$

Temperature effects

[T. Binder, LC, K. Mukaida '18]



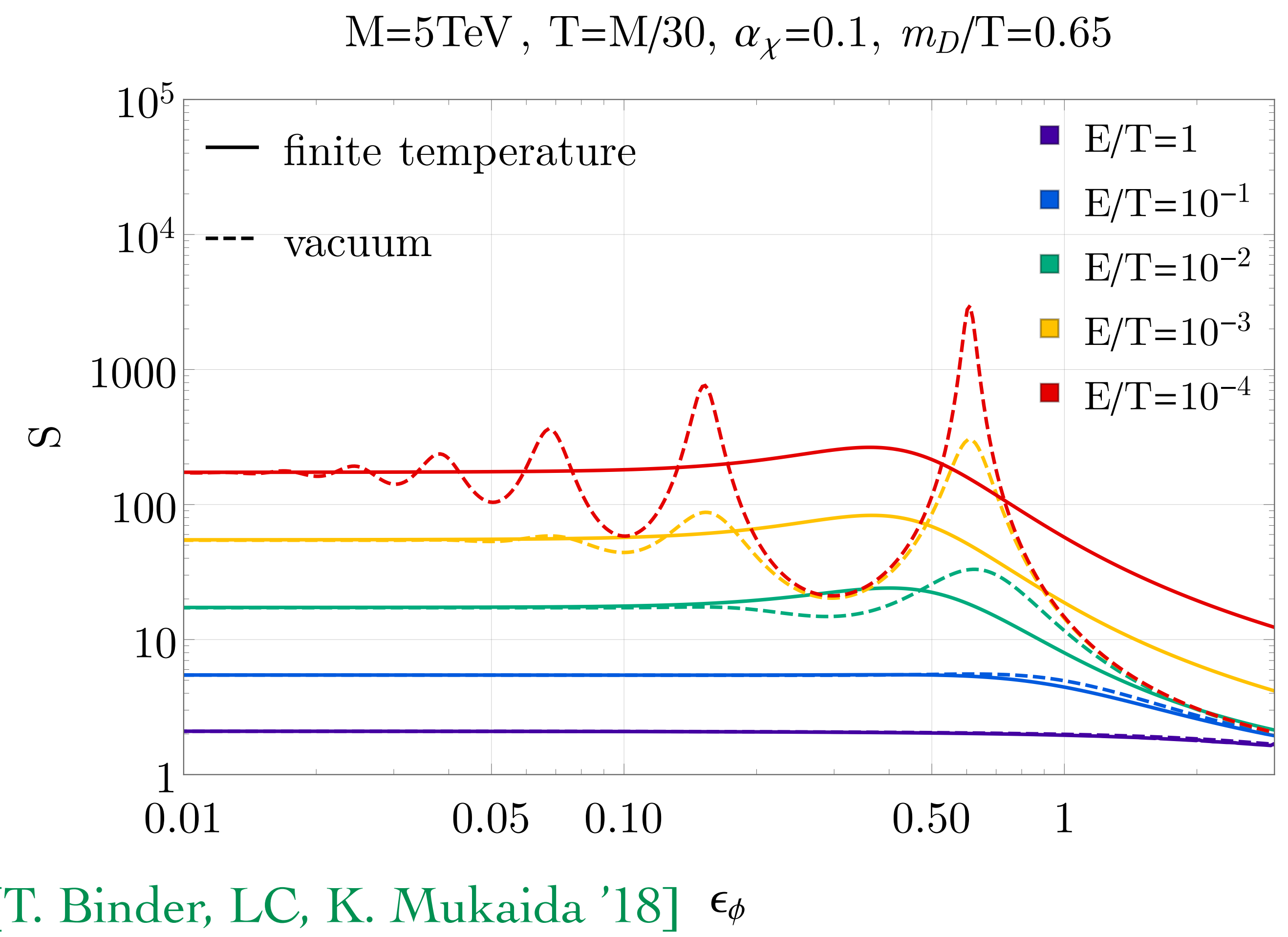
Without thermal corrections we recover the known results.



The presence of a plasma strongly modifies the bound states ! Even to the point of complete melting…

Sommerfeld enhancement

For the scattering states in a simple Yukawa potential (but practically same as gauge theory at finite T): resonances are suppressed !

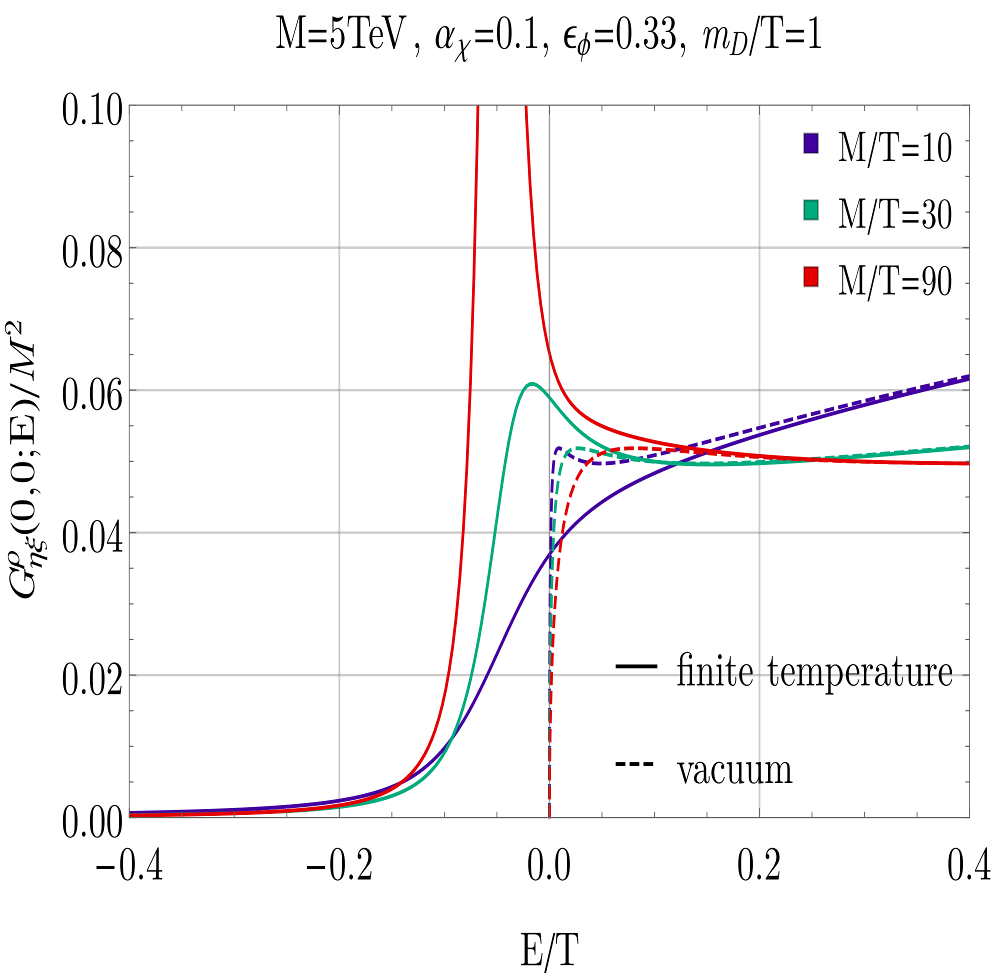


[T. Binder, LC, K. Mukaida '18]

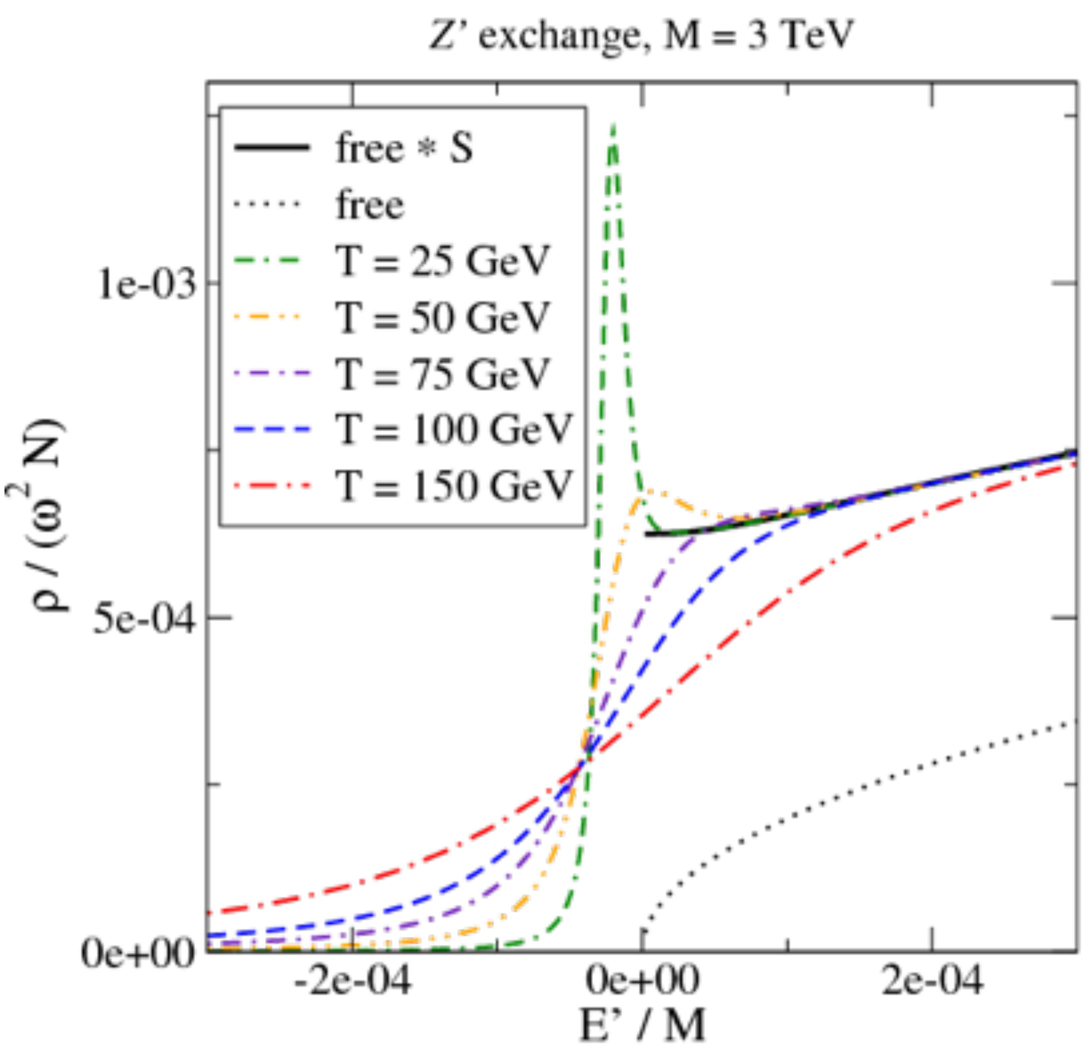
We agree with results obtained in linear response and from coupled Boltzmann equations or Kadanoff-Baym eq. (up to ionization equilibrium) [S. Kim & M. Laine 16/17 , K. Petraki, M. Postma et al 14/15, M. Beneke, F. Dighera & A. Hryczuk 14]

Comparison with previous results

[T. Binder, LC, K. Mukaida '18]



[S. Kim & M. Laine '17]



For the case of the ground state at E=0 threshold.

Co-genesis

Baryogenesis & SW DM

[Arcadi, LC & Nardecchia 1312.5703]

Generate both DM and baryon asymmetry from the decay of a mother particle. This is quite natural for the case of gravitino DM (SuperWIMP mechanism!). The baryon and DM densities are naturally of comparable order due to the comparable 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

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

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

independent of Bino density

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

Baryogenesis in RPV SUSY

RPV superpotential includes couplings that violate baryon number and can be complex, i.e.

$$W = \lambda''_{ijk} U_i D_j D_k$$

Possible to generate a baryon asymmetry from out-of-equilibrium decay of a superparticle into channels with different baryon number, e.g. for a neutralino

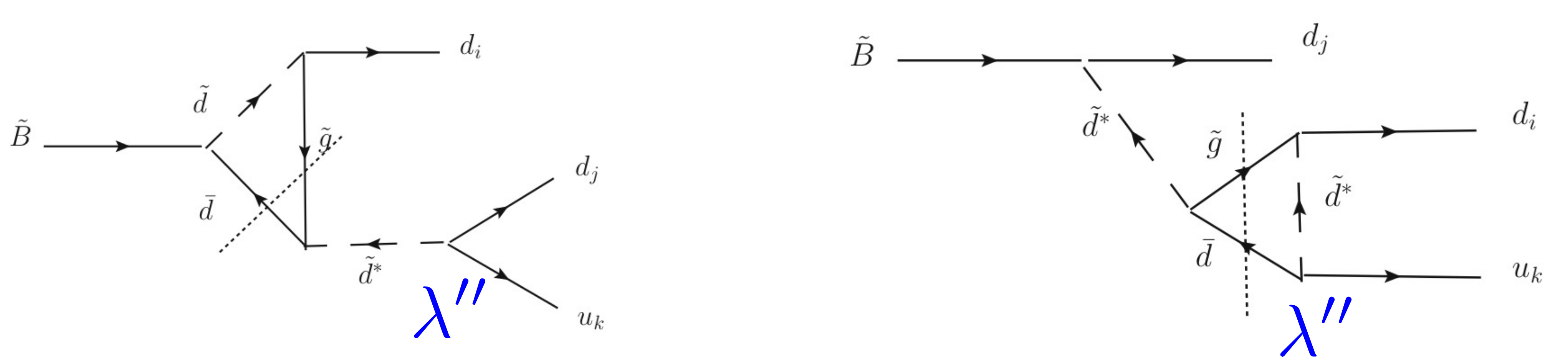
$$\tilde{B} \to udd,\ \bar{u}\bar{d}\bar{d},\ \tilde{g}\bar{q}q$$

Initial density of neutralino can arise from usual WIMP mechanism, since the decay rate is very suppressed !

Baryogenesis in RPV SUSY

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

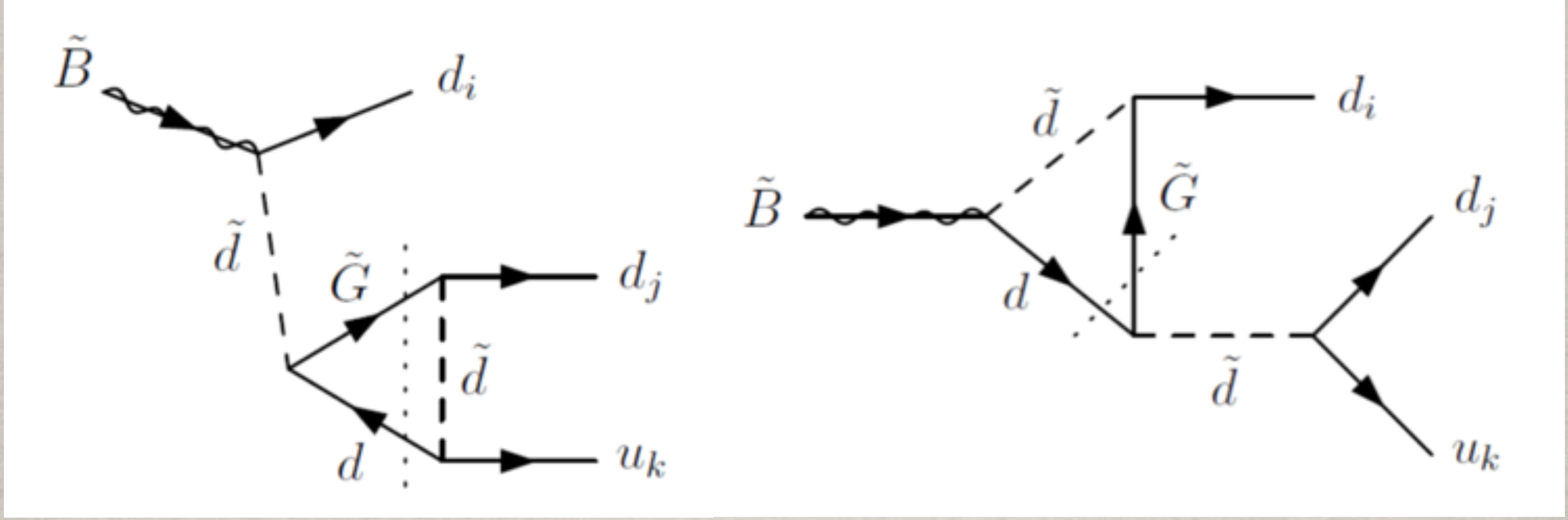
Realization of good old baryogenesis via out-of-equilibrium decay of a superpartner, possibly WIMP-like, e.g. in the model by Cui with Bino decay via RPV B-violating coupling.



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...

CP violation in RPV SUSY

Some of the loop diagrams contributing to the CP violation are



CP violation can be provided either by a phase difference between the Bino and Gluino masses or by flavour effects in the RPV couplings and CKM-mixing for squarks. The latter suffers unfortunately of GIM-like cancellations for degenerate squarks... Study of full flavour structure with general squark mass spectrum is on-going [G. Arcadi, LC & S.Khan work in progress]

Baryogenesis in RPV SUSY

Simple scenario with no Flavour Violation: the CP phase comes from the gaugino mass phase difference

$$\Gamma\left(\tilde{B} \to udd + \overline{udd}\right) = \frac{\lambda^2 g_1^2 N_{\rm RPV}}{768\pi^3} \frac{m_{\tilde{B}}^5}{m_0^4}$$

$$\Gamma\left(\tilde{B} \to \tilde{g} f \overline{f}\right) = \frac{(g_1 g_3 Q_f)^2 N_{\rm RPC}}{256\pi^3} \frac{m_{\tilde{B}}^5}{m_0^4}$$

$$\longrightarrow \quad \epsilon_{\rm CP} = \frac{8}{3} Im\left[e^{i\phi}\right] \boxed{\frac{m_{\tilde{B}} m_{\tilde{g}}}{m_0^2}} \alpha_s \left(1 + \frac{2\pi N_{\rm RPC} \alpha_s}{N_{\rm RPV} \lambda^2}\right)^{-1}$$

Baryon Asymmetry

CP asymmetry is suppressed both for $m_{\tilde{g}} = m_{\tilde{B}}$ or $m_{\tilde{g}} = 0$

Neglecting wash-out processes we get

$$\Omega_{\Delta B} \approx 1.3 \times 10^{-2} \frac{x_{\rm f.o.}}{A(x_{\rm f.o.})} \left(\frac{m_{\tilde{B}}}{1{\rm TeV}}\right) \left(\frac{\mu}{10^{3/2} m_0}\right)^2 \left(\frac{\lambda^2 N_{\rm RPV}}{\pi N_{\rm RPC} \alpha_s}\right) \left(1 + \frac{\lambda^2 N_{\rm RPV}}{\pi N_{\rm RPC} \alpha_s}\right)^{-1}$$

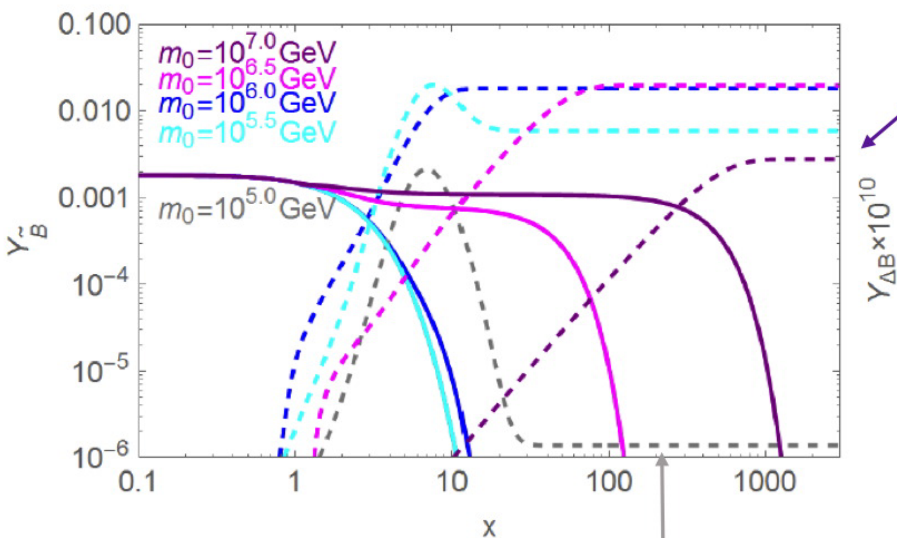
Need a very heavy spectrum to realize the scenario !

Baryogenesis in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

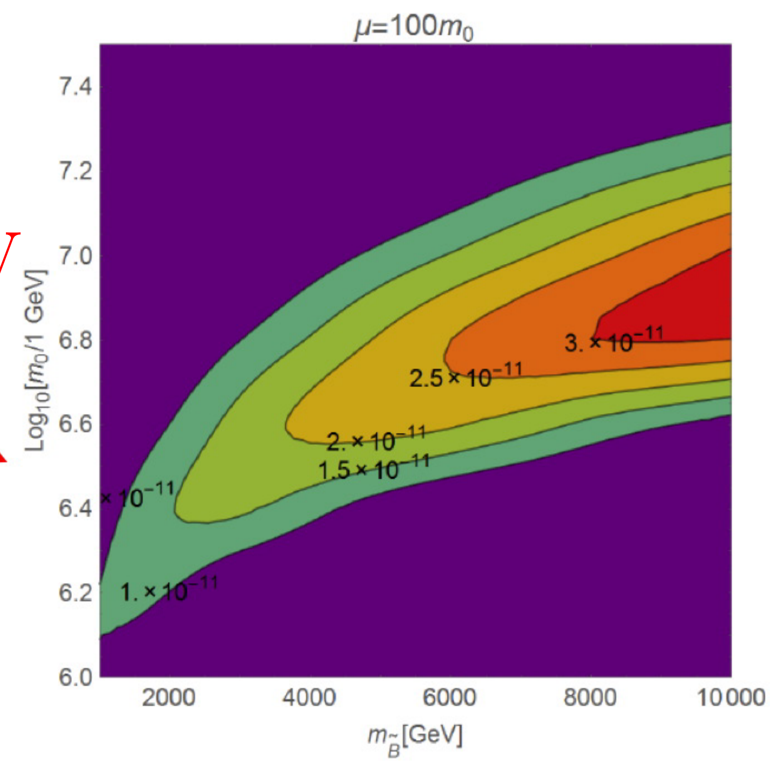
Unfortunately realistic models are more complicated than expected: wash-out effects play a very important role !!!

Asymmetry suppressed by the high scalars



Asymmetry suppressed by wash-out

10^7GeV



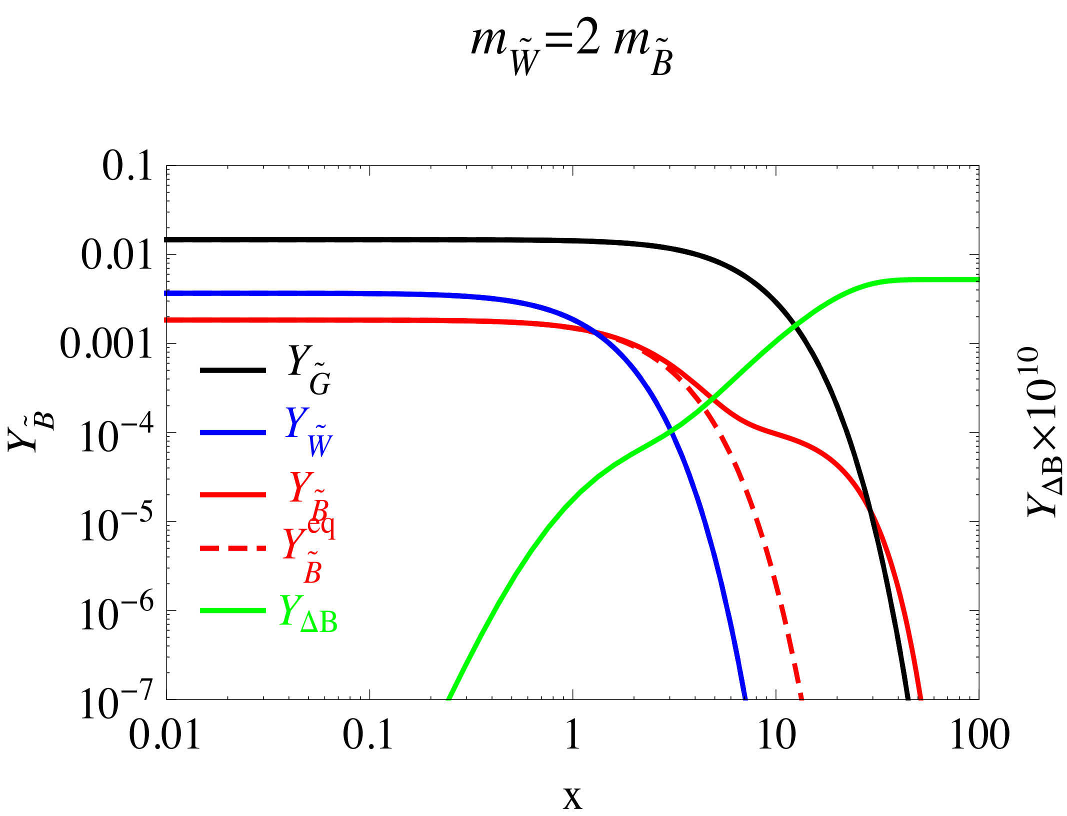
Rather definite prediction for range of scalar masses

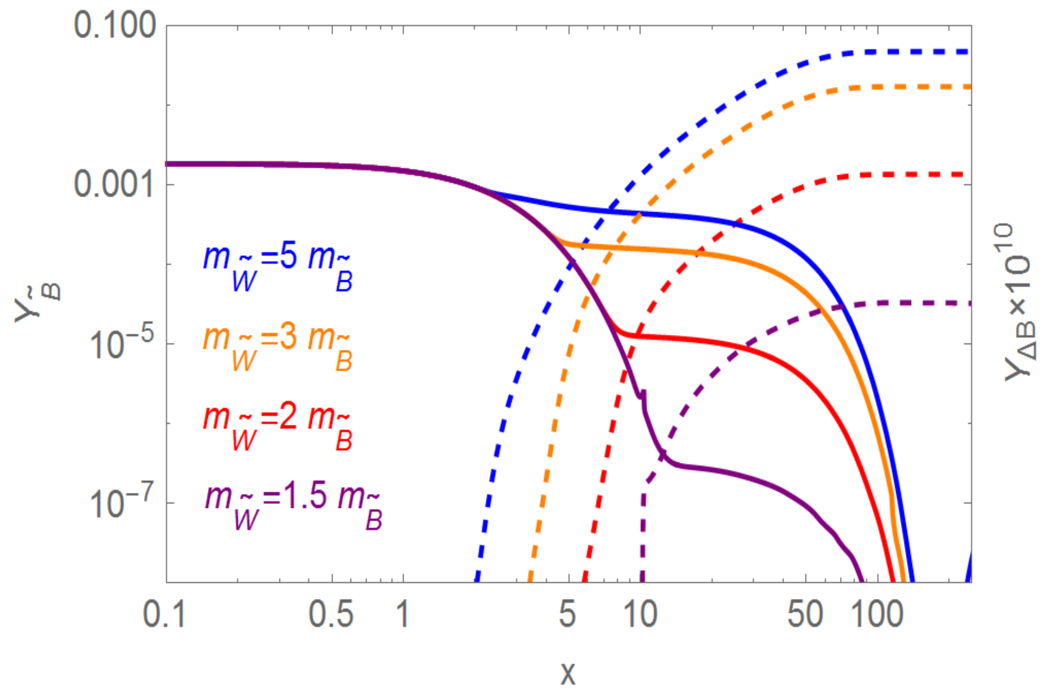
Heavy !!!

The revenge of the Wino

[Arcadi, LC & Nardecchia 1507.05584]

Main contribution to the wash-out processes comes from the Wino, which can also coannihilate with the Bino !!!





The Wino has to be sufficiently heavy to avoid keeping Bino in equilibrium and suppressing its density !

The revenge of the Wino II

[Arcadi, LC & Nardecchia 1507.05584]

But with very heavy Wino, another problem arises: the gravitino can be overproduced by freeze-in from the Wino ! Same problem with the heavy squarks, but there one could think that they are too heavy to be in thermal equilibrium...

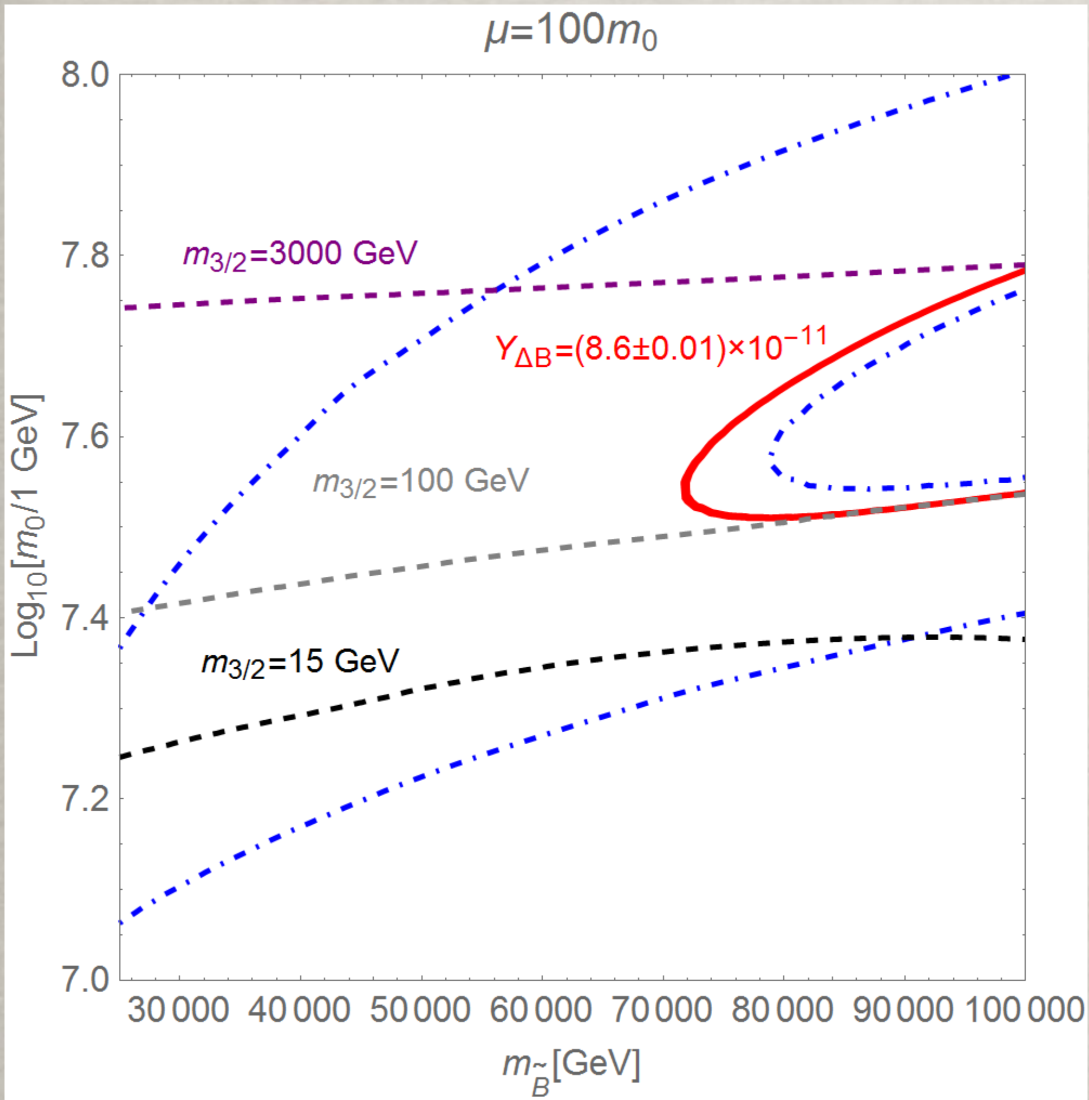
$$\Omega^{FI}_{3/2} h^2 \sim 0.002 \left(\frac{m_{\tilde{W}}}{10 \text{ TeV}} \right)^3 \left(\frac{m_{3/2}}{1 \text{ TeV}} \right)^{-1}$$

$$\longrightarrow \quad m_{\tilde{W}} < 362 \text{ TeV} \left(\frac{m_{3/2}}{1 \text{ TeV}} \right)^{1/3}$$

SuperWIMP production of DM, together with baryogenesis, is realized only in a small window of Wino masses.

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]



Moreover the large scalar mass suppresses the branching ratio into gravitinos too much…

$$BR(\tilde{B} \to \psi_{3/2} + \text{any}) << \epsilon_{CP}$$

Need a large gravitino mass to compensate & obtain $\Omega_{DM} \sim 5\, \Omega_B$, not so simple explanation after all…, but still possible with $m_{3/2} < m_{\tilde{g}}$.

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

Thanks to the large gravitino mass, the squark mass suppression is partially compensated and a visible gravitino decay is possible:

$$\Gamma(\psi_{3/2} \to u_k d_i d_j) = \frac{3\lambda^2}{124\pi^3} \frac{m_{3/2}^7}{m_0^4 M_P^2}$$

$$\tau_{3/2} = 0.26 \times 10^{28}\mathrm{s} \left(\frac{\lambda}{0.4}\right)^{-2} \left(\frac{m_{3/2}}{1\mathrm{TeV}}\right)^{-7} \left(\frac{m_0}{10^{7.5}\mathrm{GeV}}\right)^{4}$$

Right ballpark for indirect DM detection, but strongly dependent on the gravitino mass...

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

- How the baryon asymmetry of the Universe arose is yet an unsolved puzzle !
- Different mechanisms can produce it, MOSTLY based on physics beyond the Standard Model ! But often baryons and DM are unrelated, not easy to explain why they have similar energy densities…
- We discussed a couple of mechanisms producing both matter densities in one go and possibly giving a dynamical understanding of their ratio.
- Still other options are open, looking forward to more data on CP violation in the neutrino sector and DM properties !