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Interacting DM and the Sommerfeld enhancement at finite Temperature

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based on work in collaboration with

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Outline

- Introduction:
  - Interacting Dark Matter
  - Sommerfeld enhancement at $T=0$
- Thermal relics and the Sommerfeld enhancement at finite temperature
- A minimal model of SU(2) interacting asymmetric DM and leptogenesis
- Outlook

Introduction

10+Billion $ Question: How does Dark Matter interact apart gravity ?

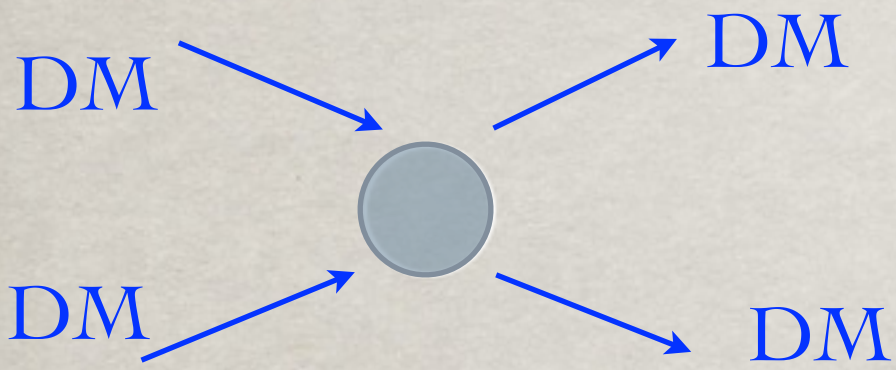
We detected DM so far only through its gravitational effects, which are universal and do not tell us what DM is !
BUT probably we some other interaction is needed to produce DM since gravity is not very effective.

Moreover the standard CDM simulations do not fare so well on the small scales...: the missing satellites, core vs cusp in dwarves galaxies, too big to fail problems may be a hint that we need to go beyond the CDM/WIMP paradigms !
[Klypin et al 1999, Moore et al 1999], [Moore 1994, Flores & Primack 1994], [Bolyan-Kolchin, Bullock & Kaplinghat 2011+2011]

Of course there is also a chance that baryons solve it all...

DM-DM INTERACTION

Self-interaction:



Bullett cluster bound on self-interaction:

$$\sigma \leq 1.7 \times 10^{-24} cm^2 \sim 10^9 pb \quad (m = 1\ \mathrm{GeV})$$

[Markevitch et al 03]

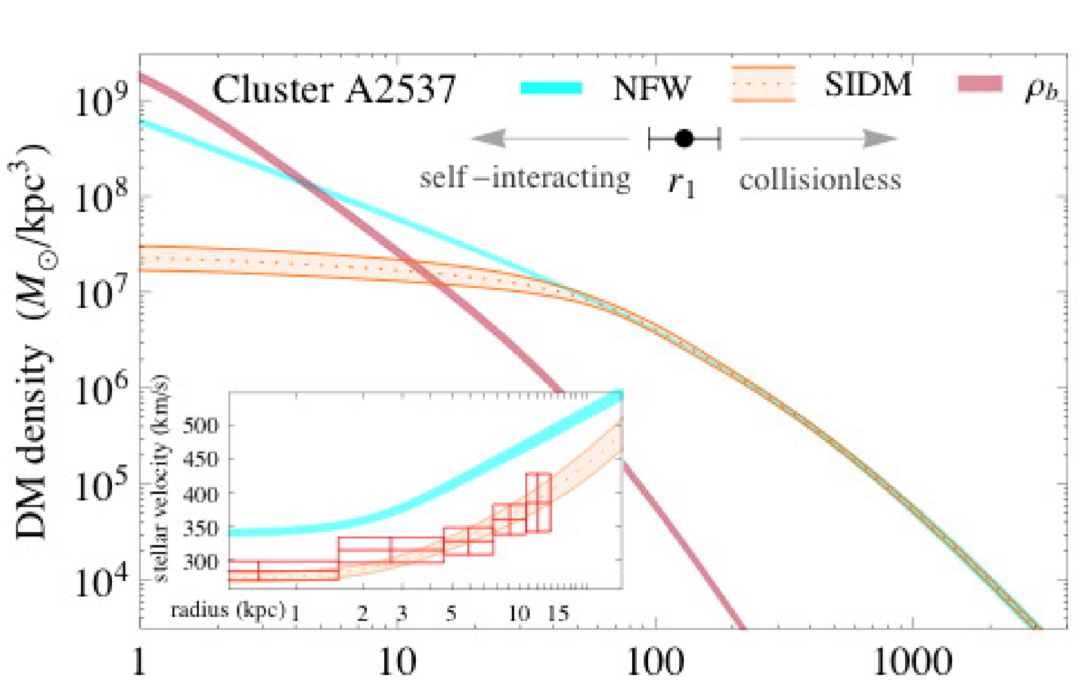
Slightly stronger constraint by requiring a sufficiently large core & from sphericity of halos... [Yoshida, Springer & White 00]

But at the boundary maybe some effect on small scales:

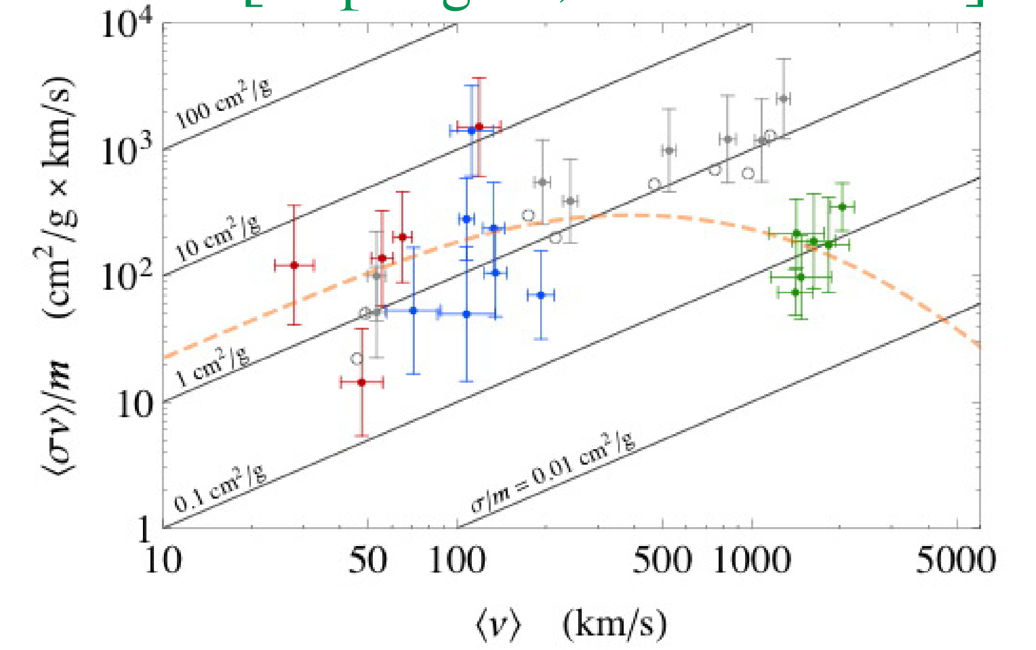
Strongly Interacting Massive Particle [Spergel & Steinhardt 99]

DM-DM INTERACTION

SIMP Dark Matter can relax some of the tensions at small scales and flatten the density in the centre:



[Kaplinghat, Tulin & Yu 15]

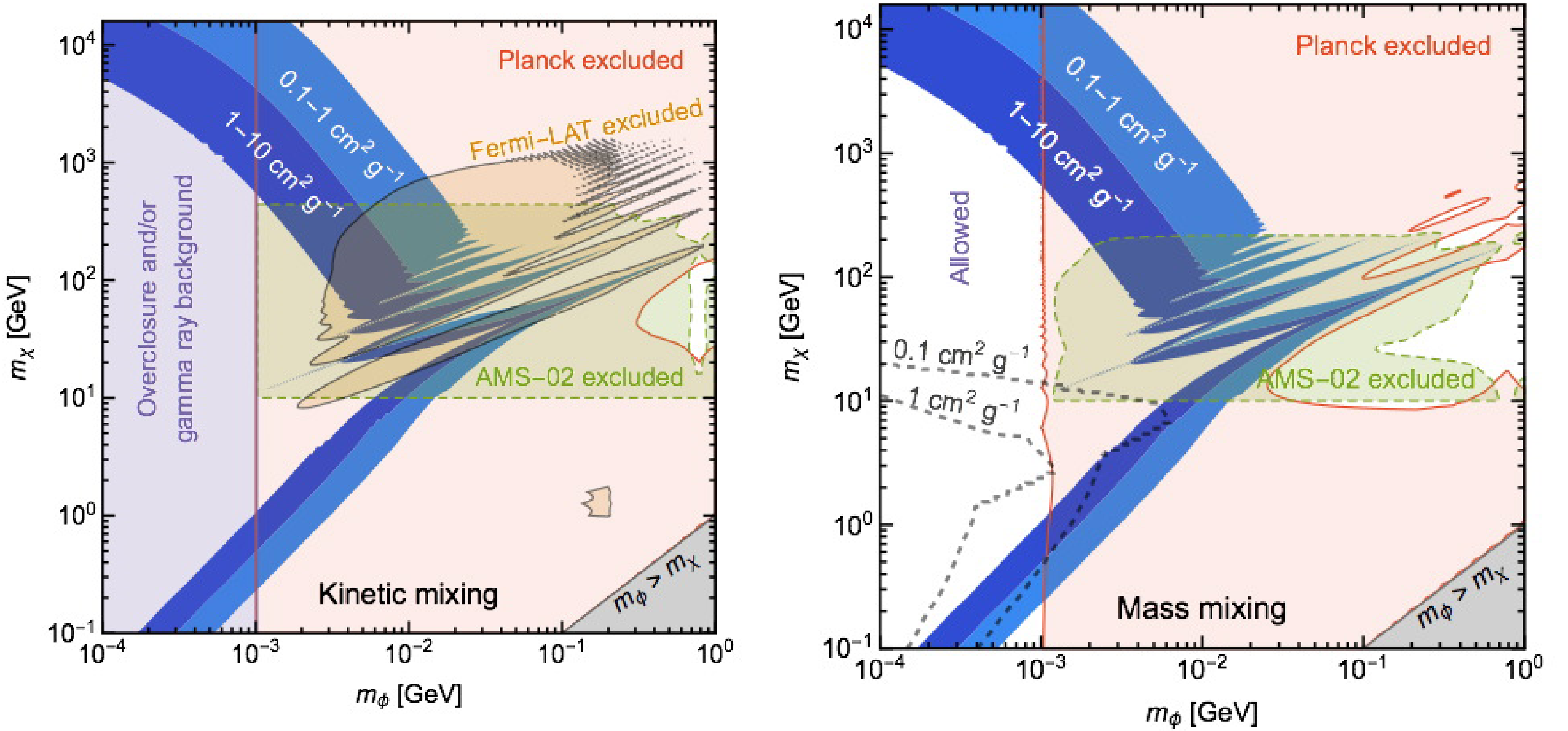


On the other hand it looks that larger cross-sections are needed at dwarves galaxies/low surface brightness galaxies compared to cluster scales… ➡ velocity dependence !

DM-DM INTERACTION

New constraints for light mediator from ID and CMB:

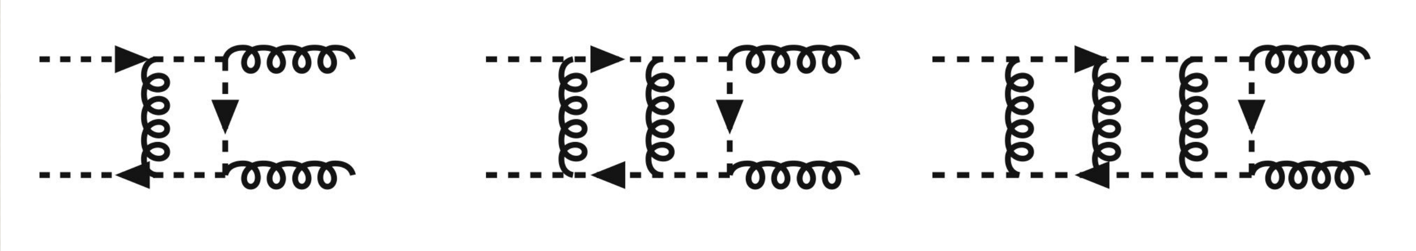
[Bringmann, Kahlhoefer, Schmidt-Hoberg and Walia 16]



S-wave annihilation into Vector with Sommerfeld effect, weaker bounds on p-wave annihilation

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:

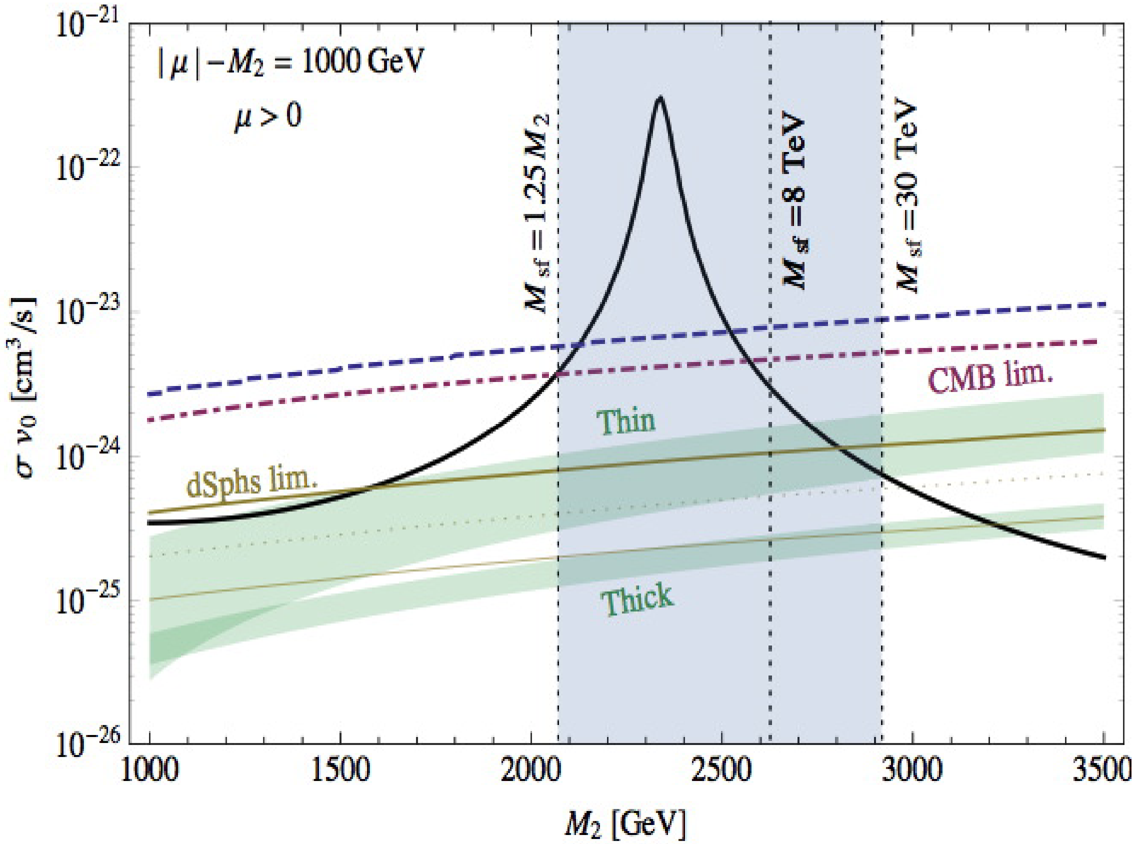
$$\sigma_S = \sigma_0 \times E_S(\beta) \qquad E_S(\beta) = \frac{z}{1 - e^{-z}} \quad \text{with} \quad z = \frac{C\pi\alpha_N}{\beta}$$

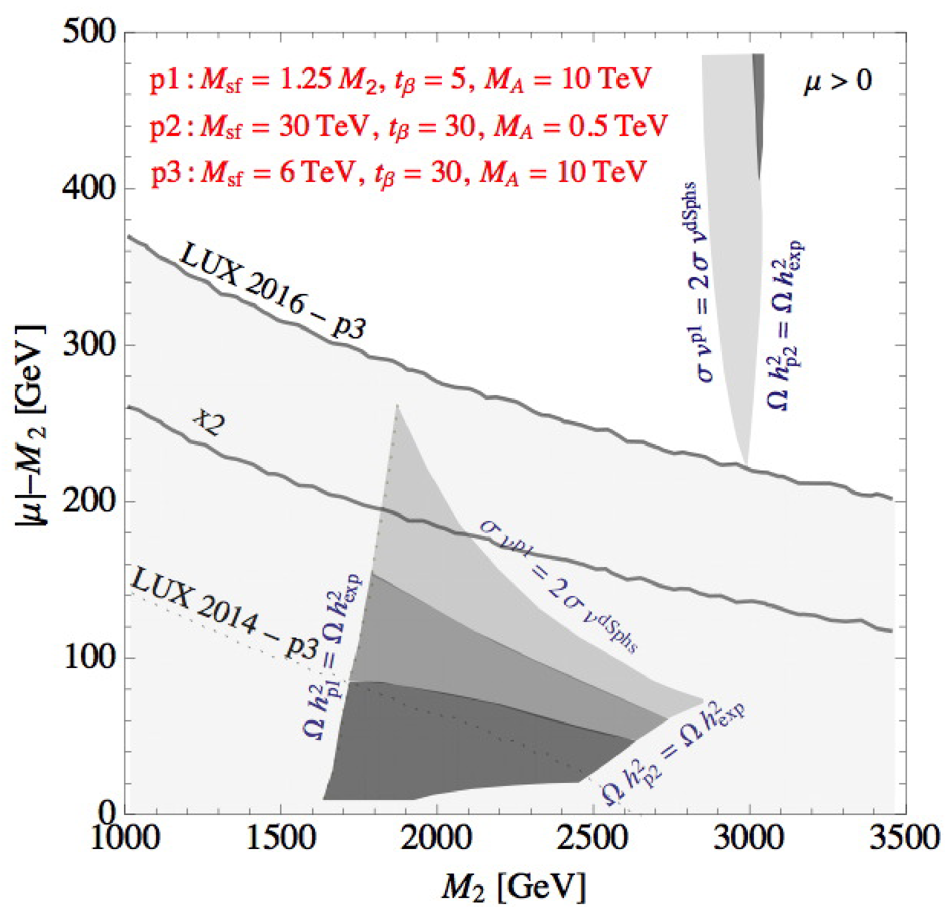
- Dominant correction for small velocity !!!
  RELEVANT AT FREEZE-OUT and TODAY !

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]





THE WIMP PARADIGM

Primordial abundance of stable massive species

[see e.g. Kolb & Turner '90]

The number density of a stable particle X in an expanding Universe is given by the Bolzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = \langle \sigma(X + X \rightarrow \text{anything})v \rangle \left(n_{eq}^2 - n_X^2\right)$$

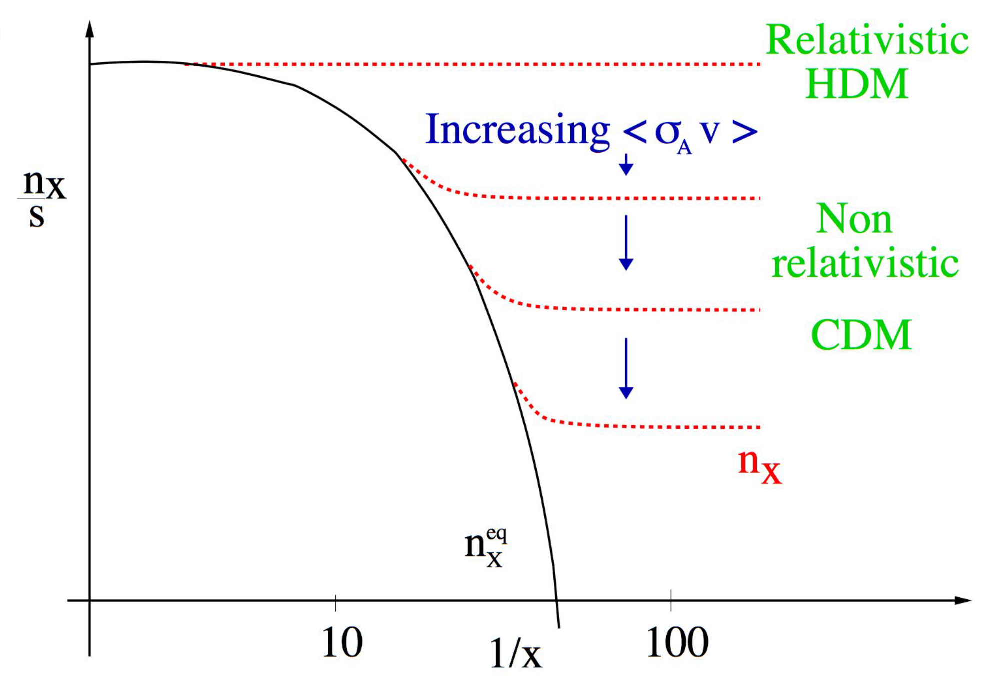
Hubble expansion   Collision integral

The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = m_X/T_f$

defined by $n_{eq} \langle \sigma_A v \rangle_{x_f} = H(x_f)$ and that gives

$$\Omega_X = m_X n_X(t_{now}) \propto \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties



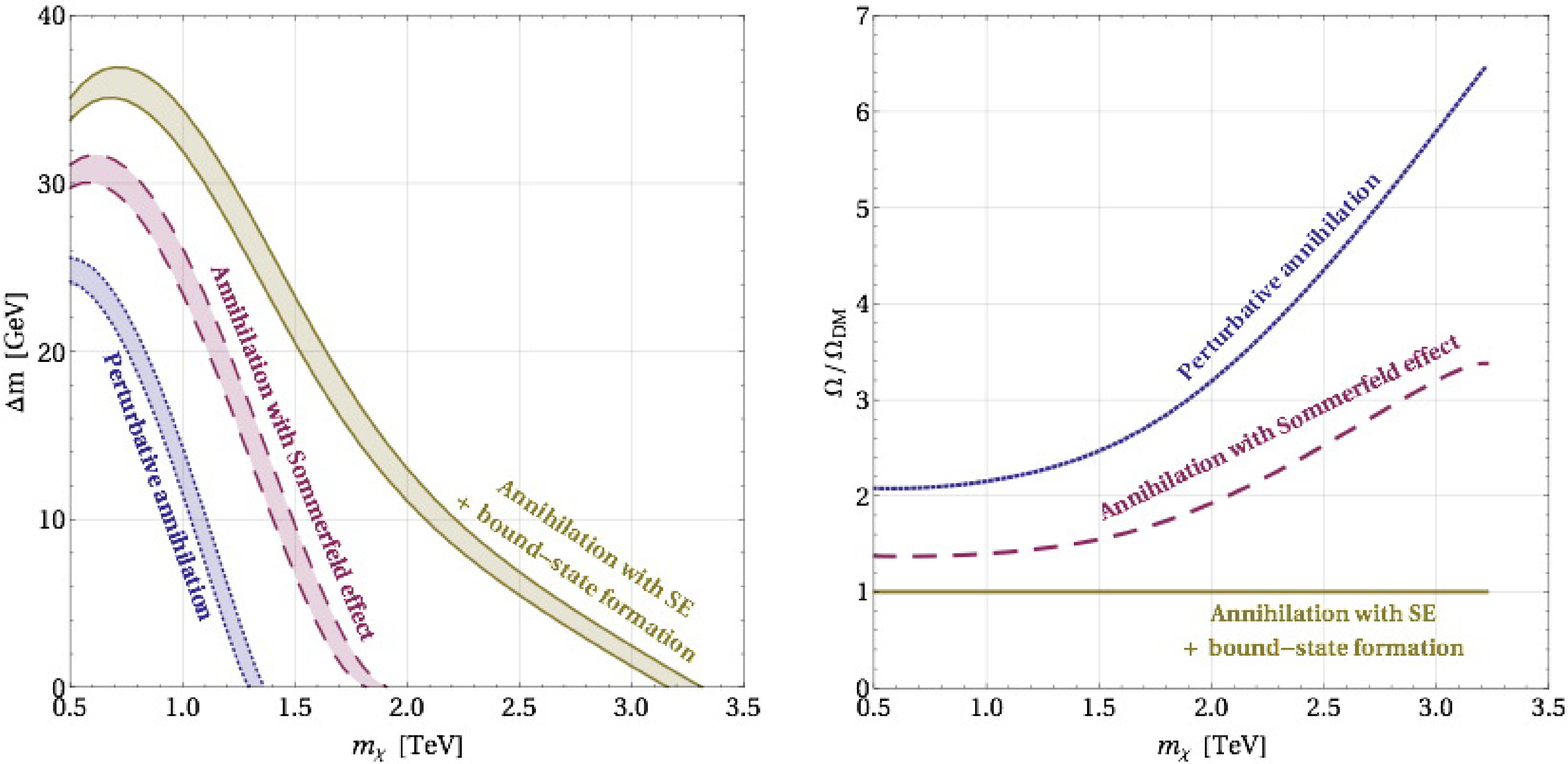
For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !

Sommerfeld Factor for coannihilation

[J. Harz & K. Petraki 2018]



Coannihilation with a colored state:bound states are important !

Sommerfeld enhancement at finite temperature

Plasma effects ?

[Berger, LC, Kraml, Palorini 08]

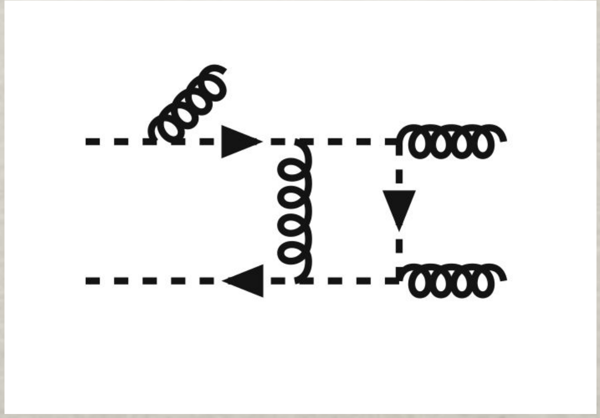
- Plasma screening/Debye thermal mass for the gluon: depends on

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

- 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....

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

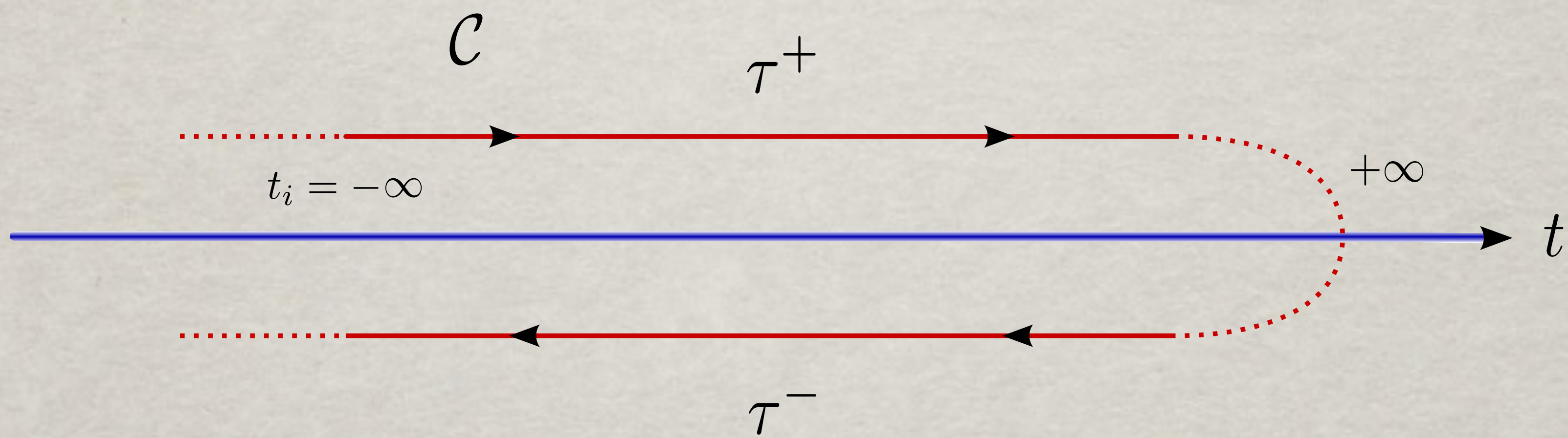
$$S \leftrightarrow A + g$$



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).

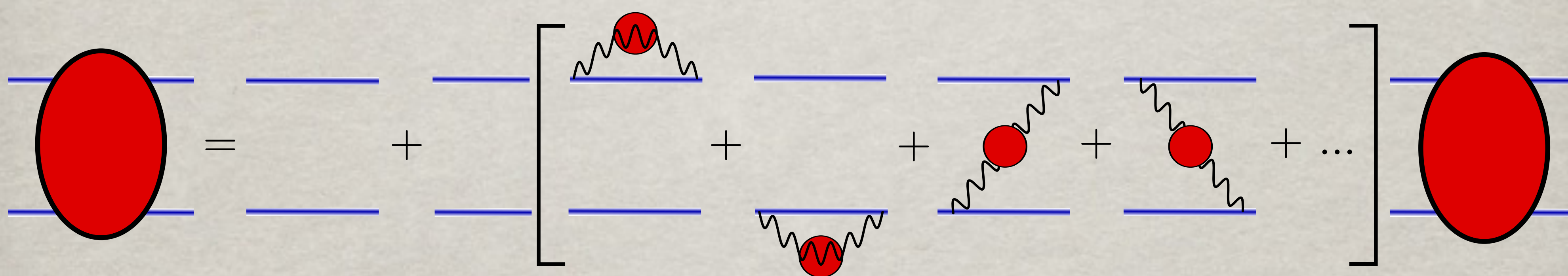
- We can write down the action for the NR Dark Matter and consider the Dyson series for the DM correlation functions;
- We close the hierarchy of equations at the level of the 4 point-function to be able to describe bound and scattering states;
- We consider the HTL resummed gauge boson propagator to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

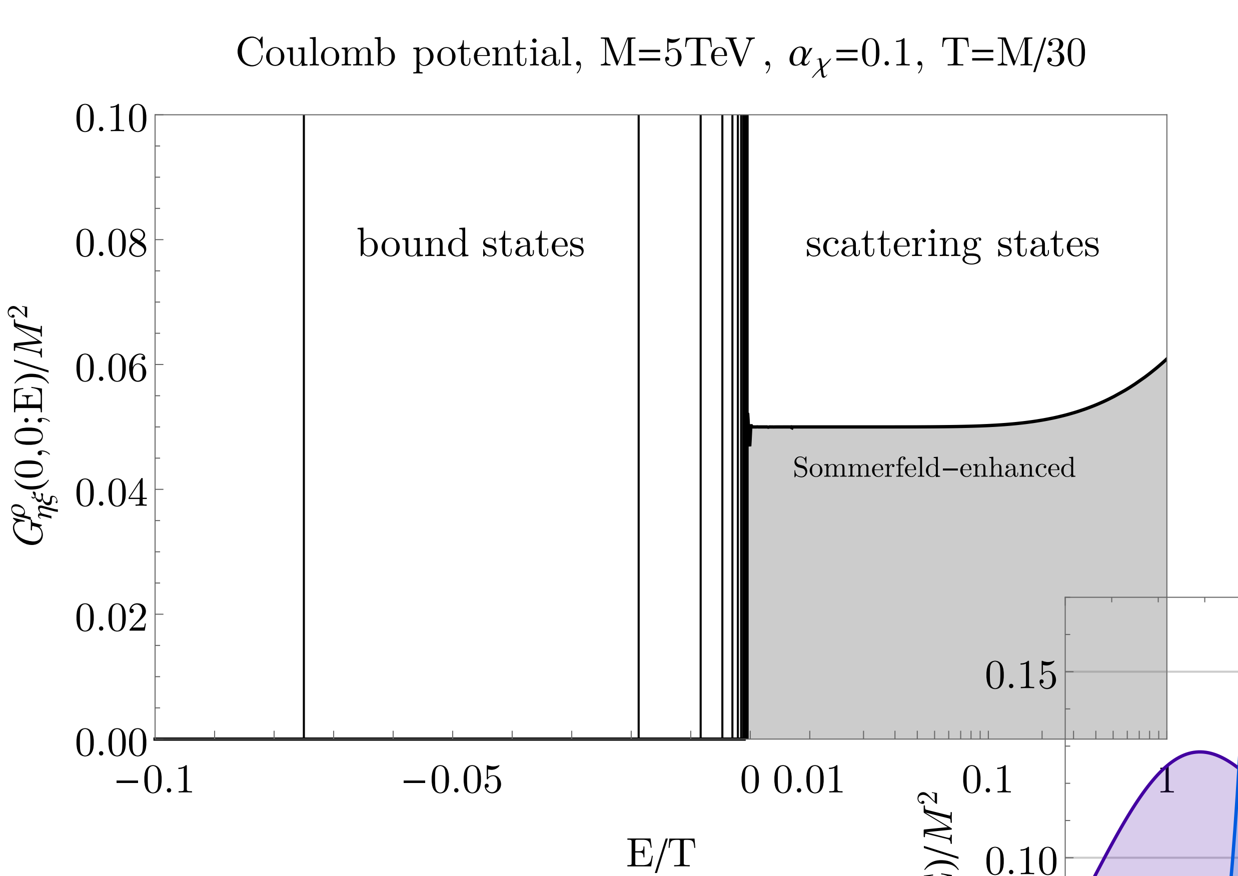
In the DM dilute limit, we obtain from this equation the modified Coulomb potential:

Yukawa-like ! Imaginary

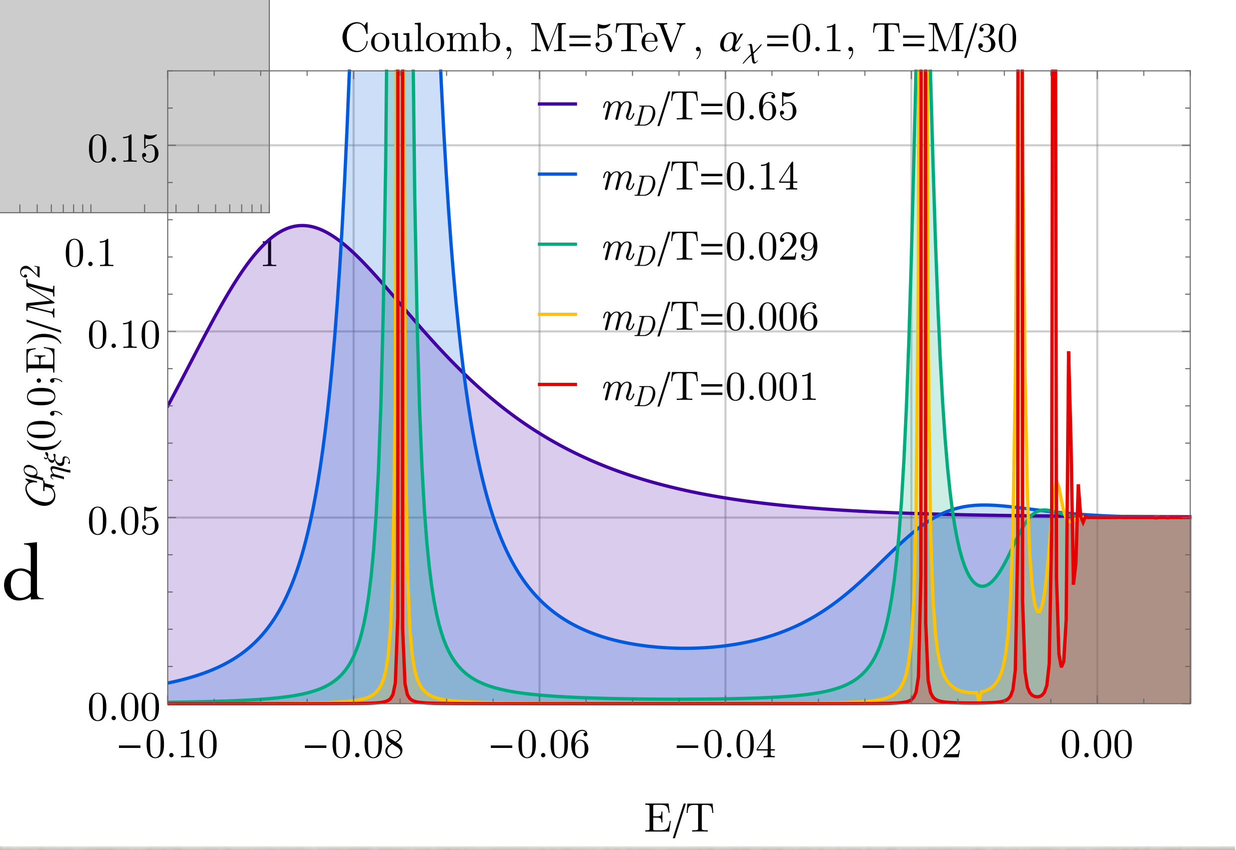
$$V_{eff}(\vec{r}) = -ig^2 \int_{-\infty}^{+\infty} d^3q(1 - e^{i\vec{q}\vec{r}})G^{++}(0, \vec{q}) = -\frac{\alpha}{r} e^{-m_D r} - i\alpha T\Phi(m_D r) + \ldots$$

Temperature effects

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



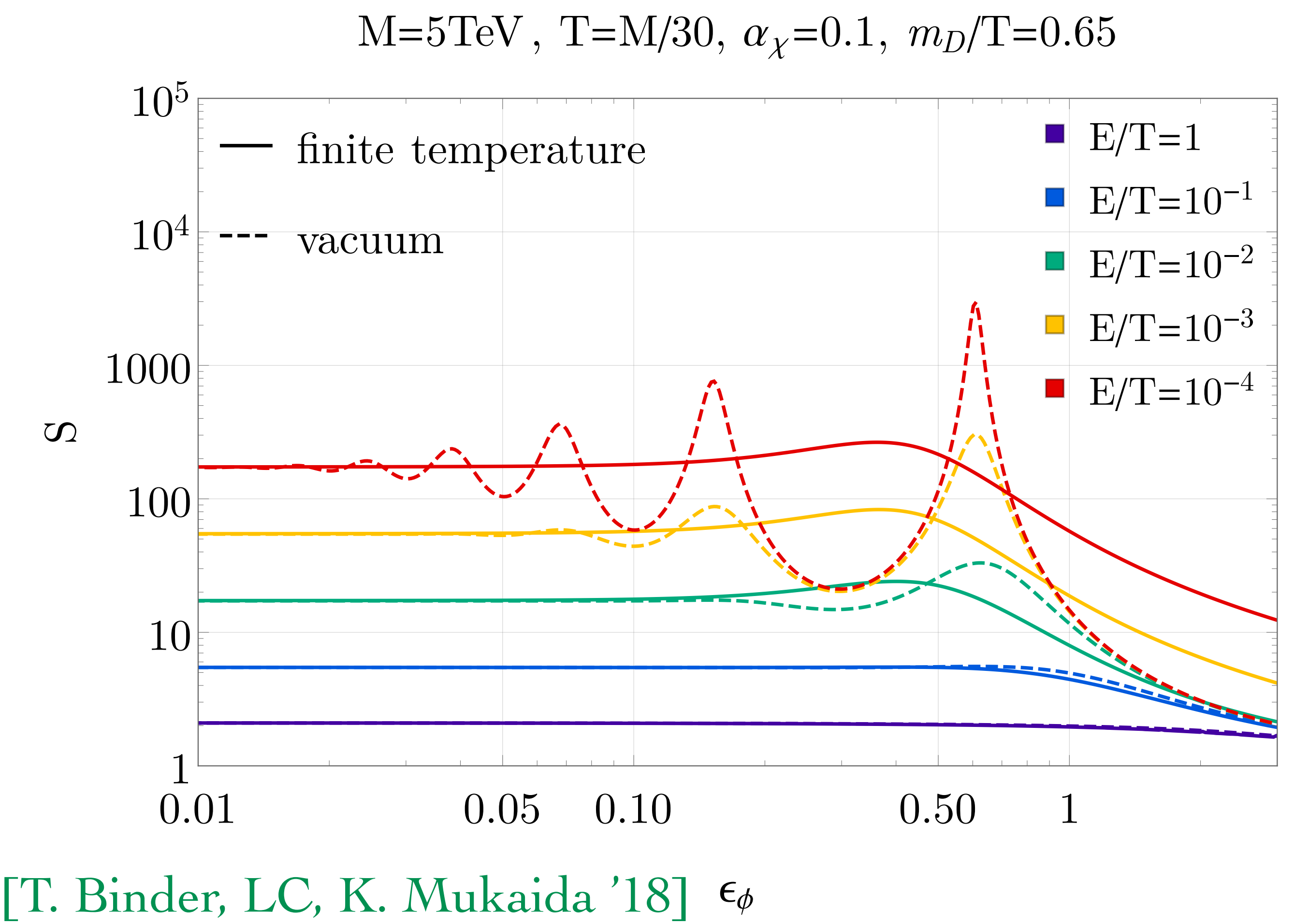
Without thermal corrections we recover the known results.



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 !

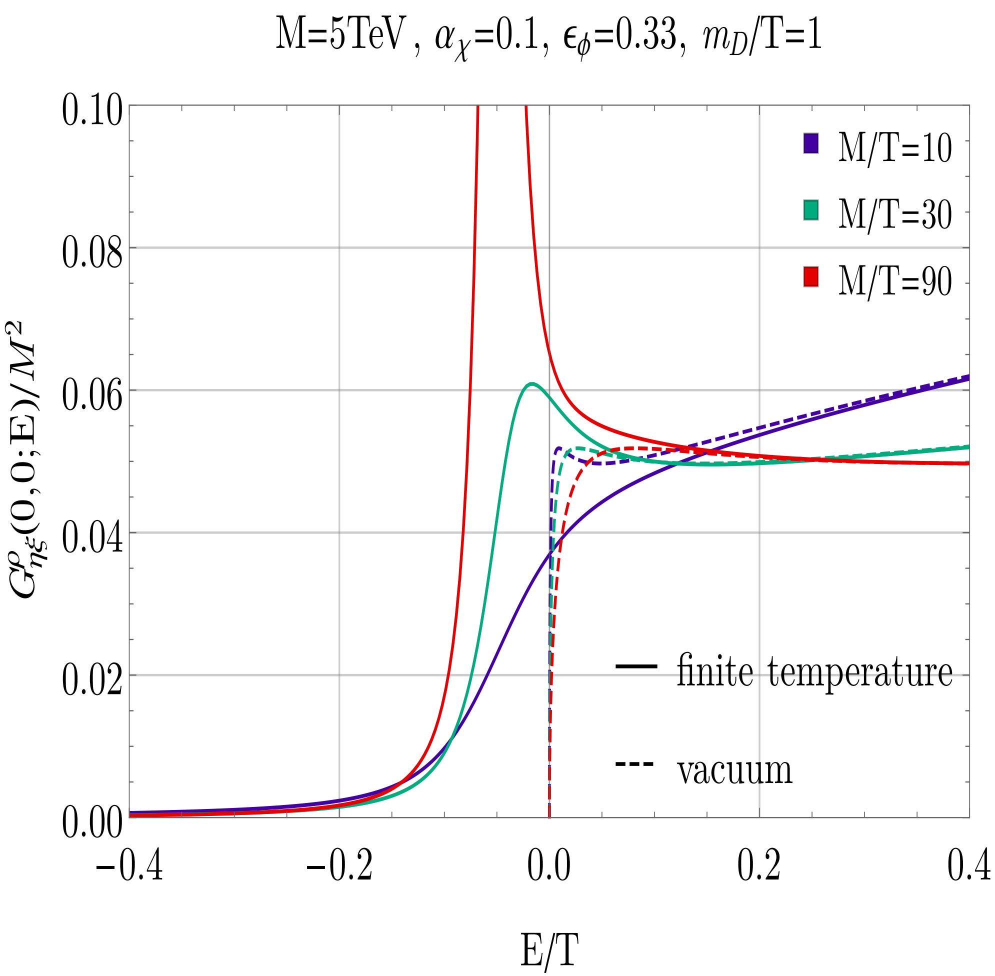


[T. Binder, LC, K. Mukaida '18]

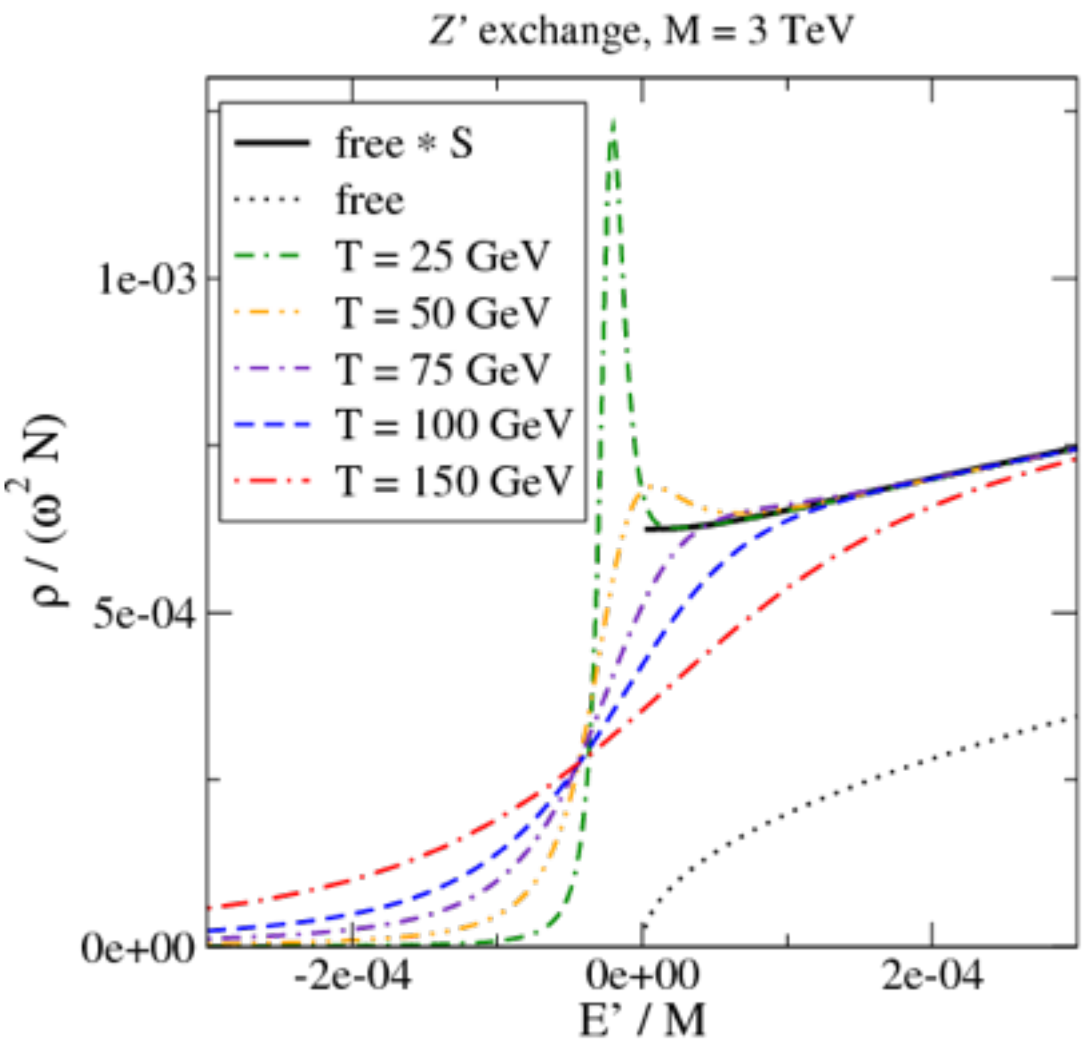
We agree with results obtained in linear response and from coupled Boltzmann equations or Kadanoff-Baym eq. (up to ionization equilibrium) [S. Kim & M. Laine 16/17 , K. Petraki, M. Postma et al 14/15, M. Beneke, F. Dighera & A. Hryczuk 14]

Comparison with previous results

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



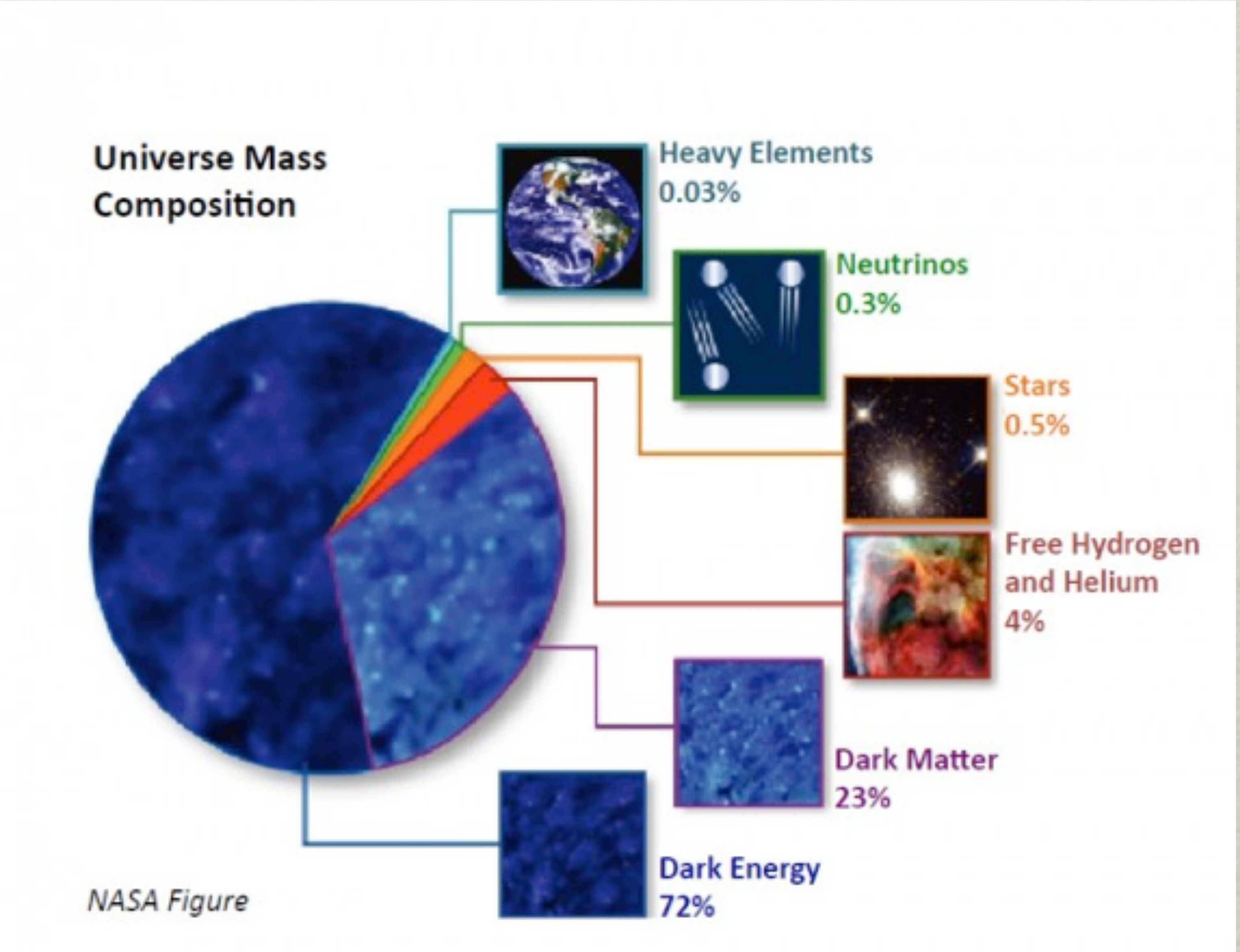
[S. Kim & M. Laine '17]



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

Minimal model for Asymmetric Dark Matter & leptogenesis

Universe composition



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

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.

$$\Psi \to B + X$$

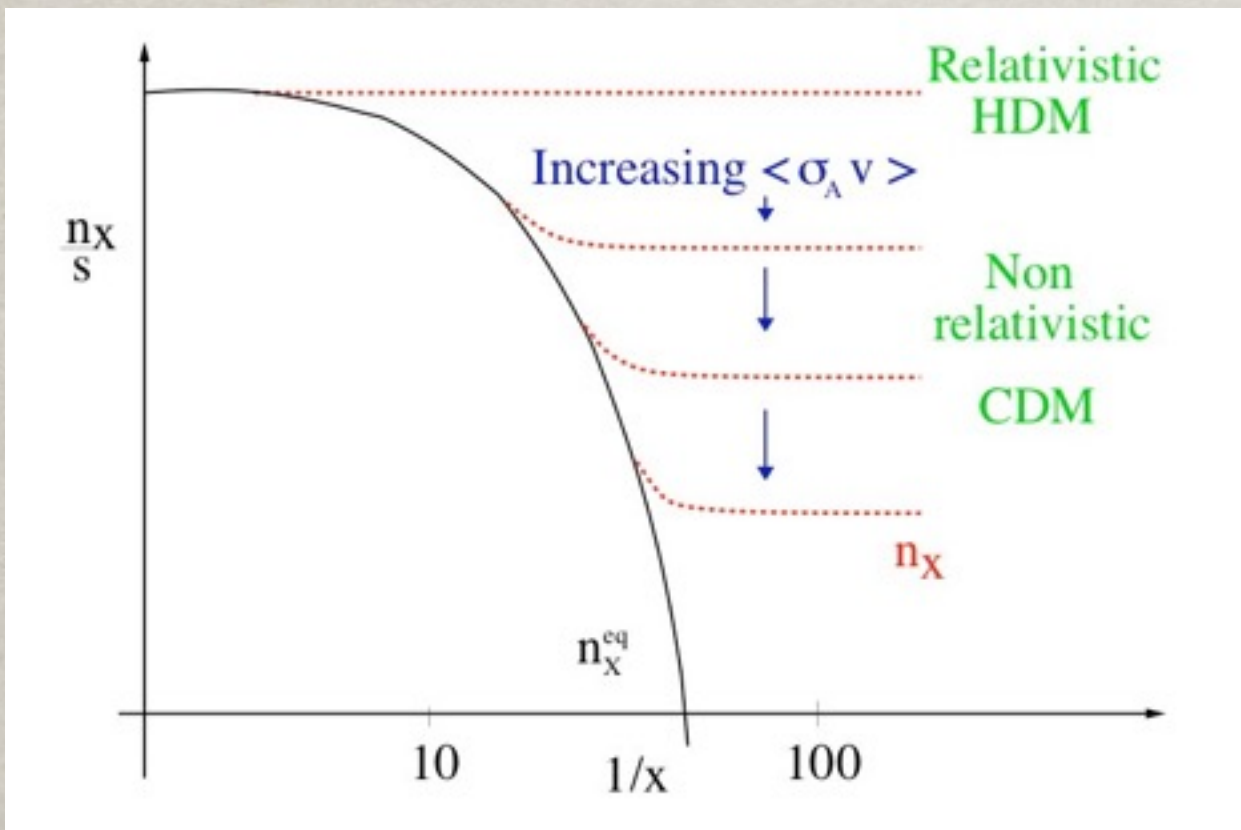
$$n_{DM} \sim n_b \to \Omega_{DM} \sim 5\,\Omega_b$$

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

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

Asymmetric Dark Matter

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 !

Or the Sommerfeld enhancement could help in annihilating efficiently !

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
$\mathbb{Z}_3 \times \mathbb{Z}_2$	$(\omega, 1)$	$(\omega, 1)$	$(\omega, 1)$	$(\omega^2, -1)$	$(\omega^2, -1)$	$(\omega^2, -1)$	$(1, 1)$	$(1, 1)$	$(1, 1)$	$(\omega, 1)$

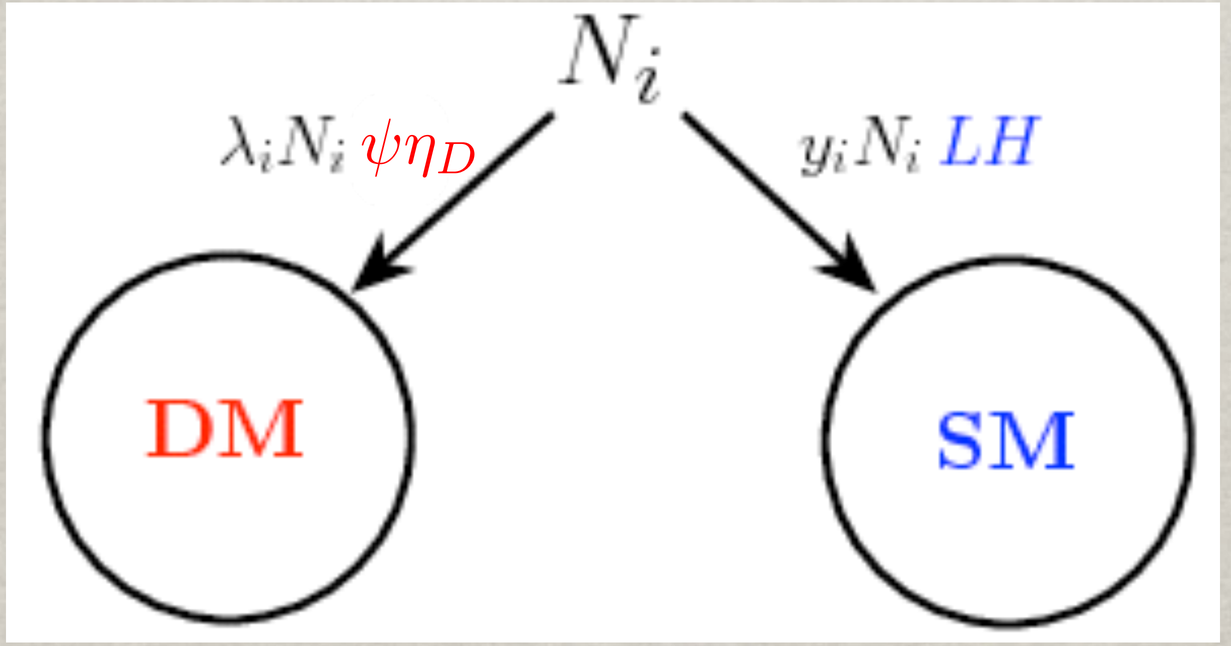
We need an additional Dark SU(2) in order to annihilate away the symmetric DM component and discrete symmetries to reduce the number of possible couplings.

Asymmetric Dark Matter

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

Falkowski, Ruderman & Volansky 2011]

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 !

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:

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

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 ! Only a single Majorana phase (for 2 RH neutrinos !) survives at low energy !

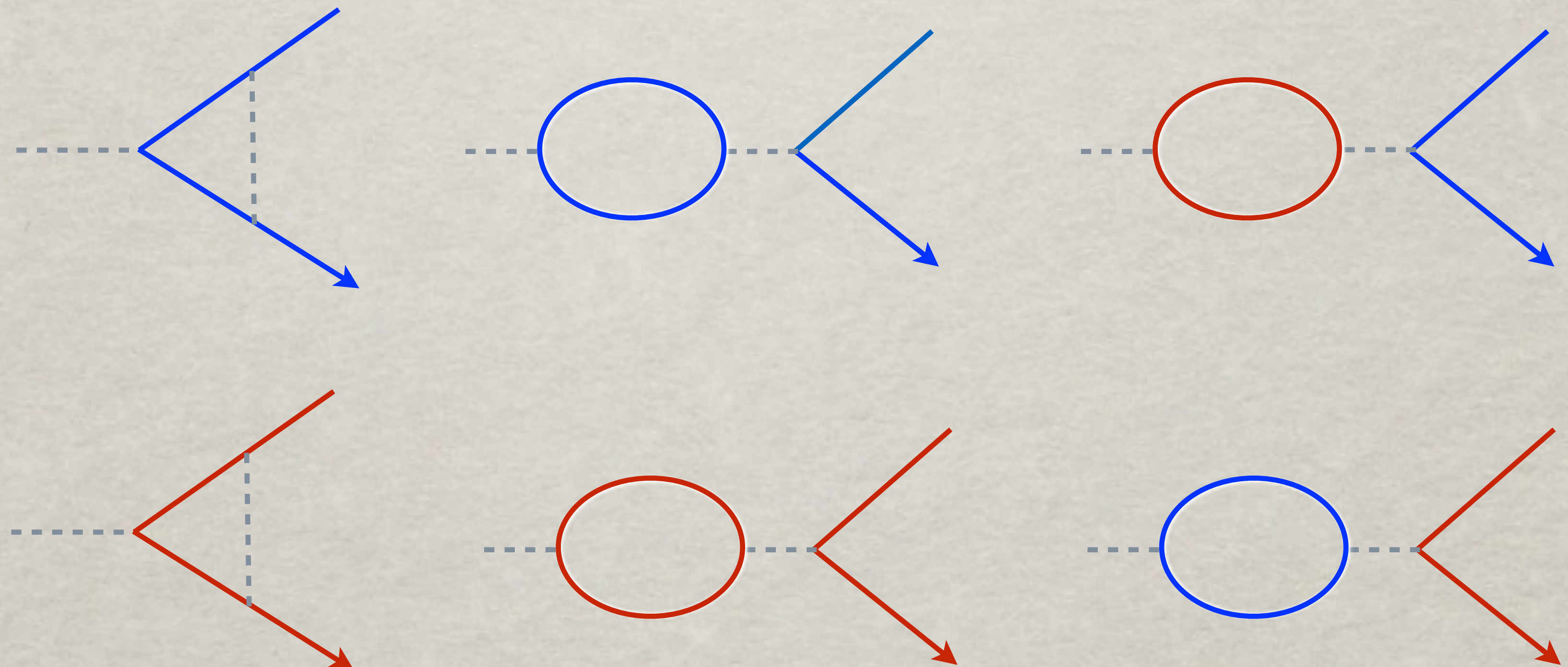
CP violation for ADM

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

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

ϵ_ℓ

ϵ_D



$$\epsilon_\ell = \epsilon_D$$

CP violation for ADM

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

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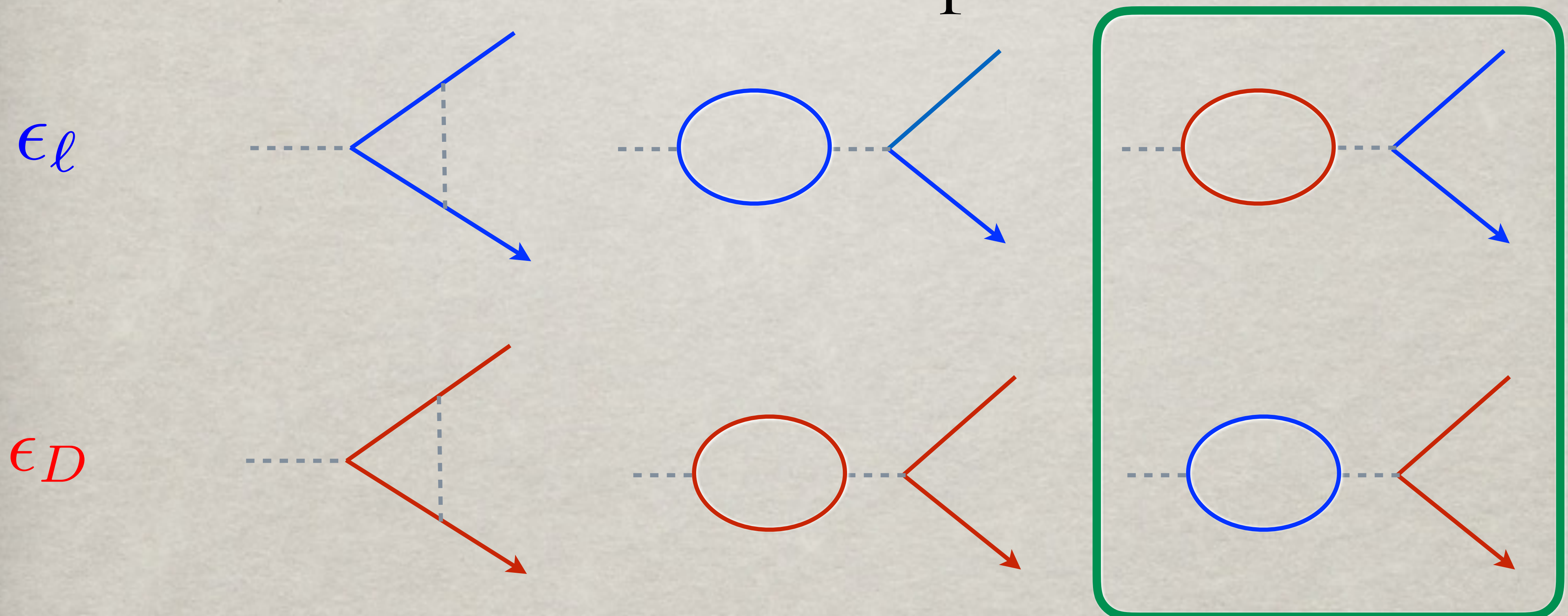


But the wave-function contribution with virtual leptons/DM can dominate both asymmetries and give $\epsilon_\ell = \epsilon_D$!

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

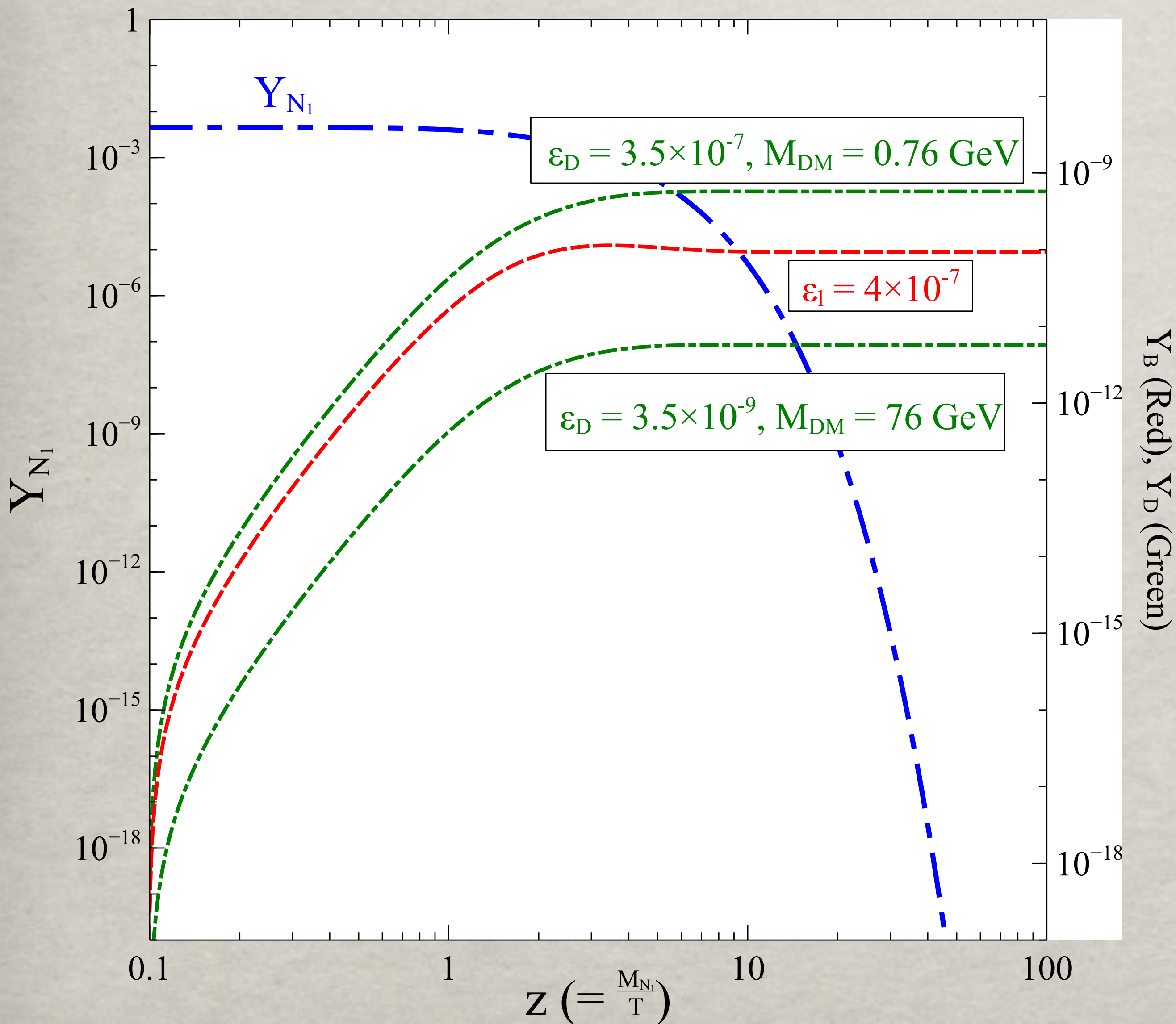
we have Real $((y^\dagger y)^*_{12})^2$ and exactly $\epsilon_\ell = \epsilon_D$.

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

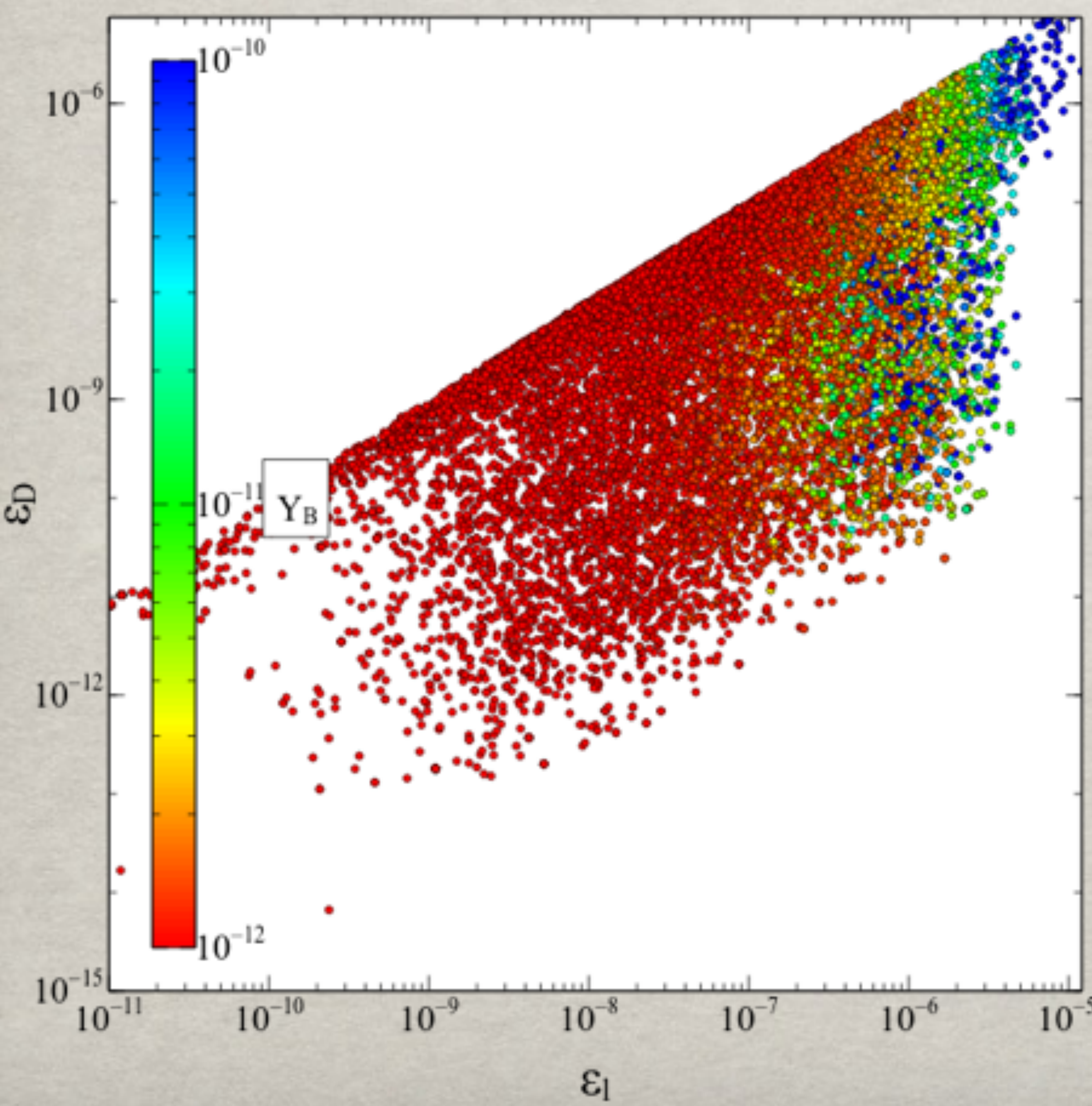
[A. Biswas, S. Choubey, LC & S. Khan 2018]



Even if the CP parameters are 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]

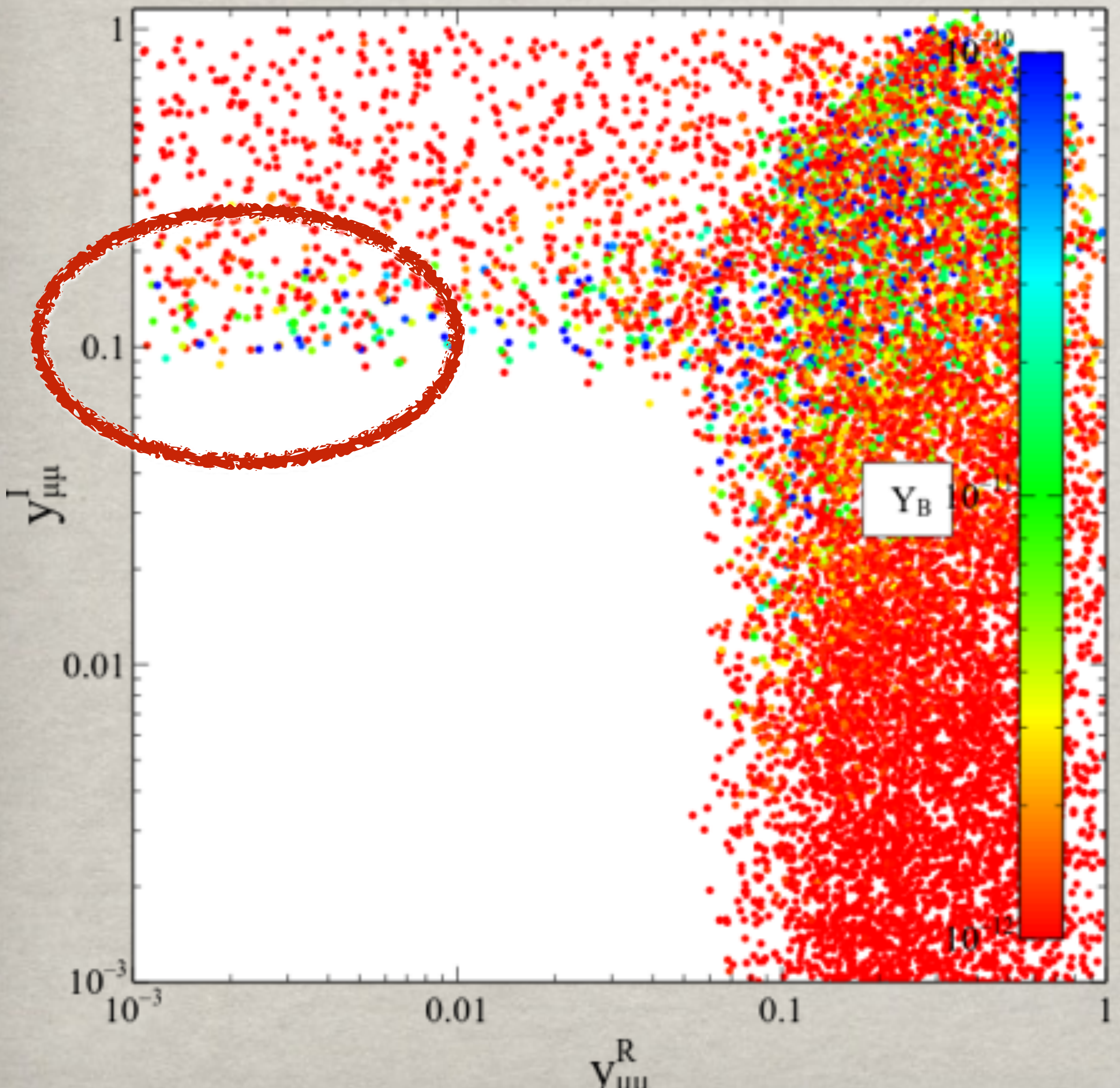


Generically need largish ϵ_ℓ in order to obtain the full baryon asymmetry.

For the Dark Sector, also smaller values are OK if we tune the DM mass to compensate, but cannot push much above TeV !

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

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

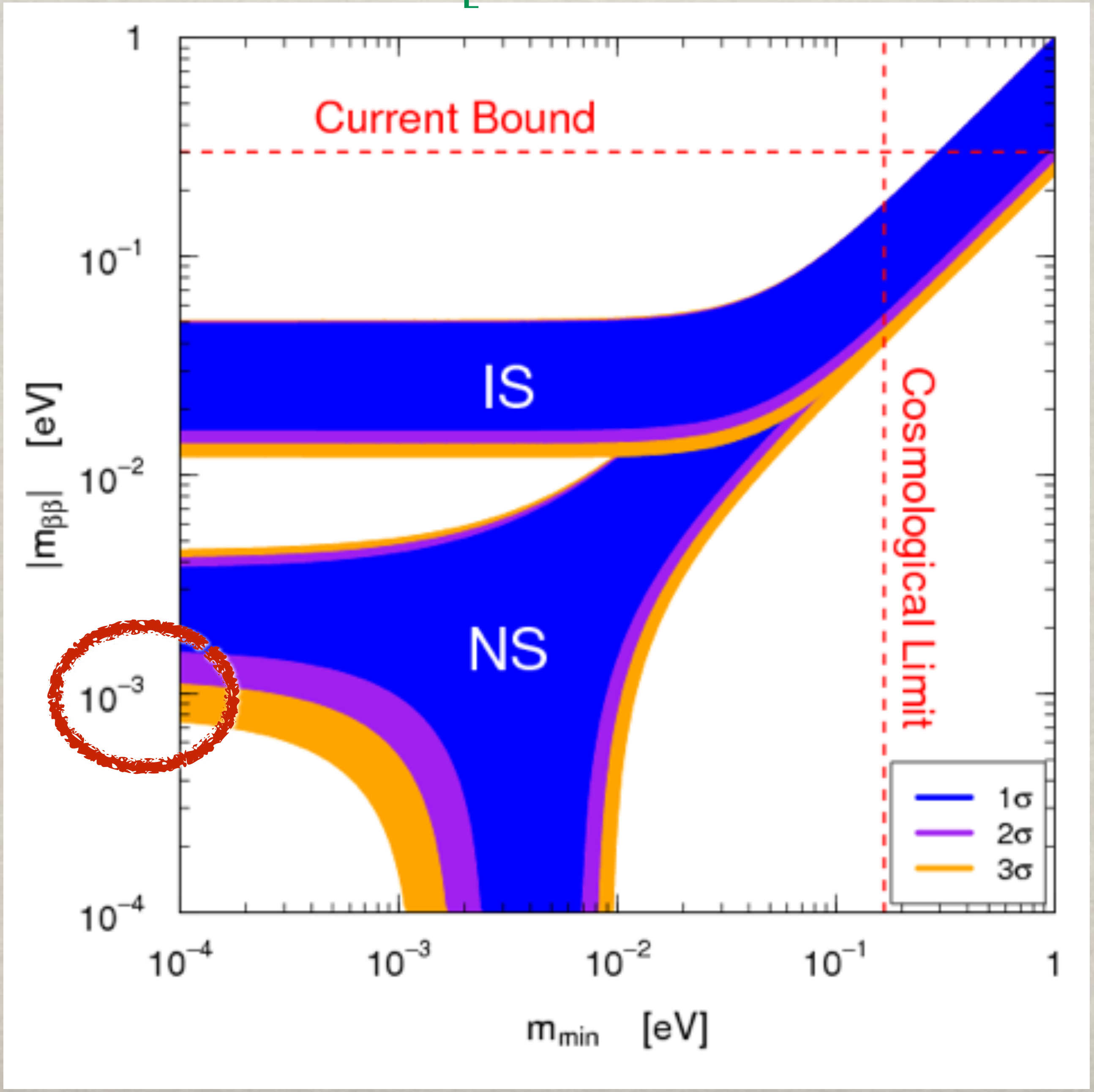
Minimal case of imaginary second column with $\delta_{CP} = 0, \alpha = \pi/2$

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

Minimal value for zero eigenvalue !

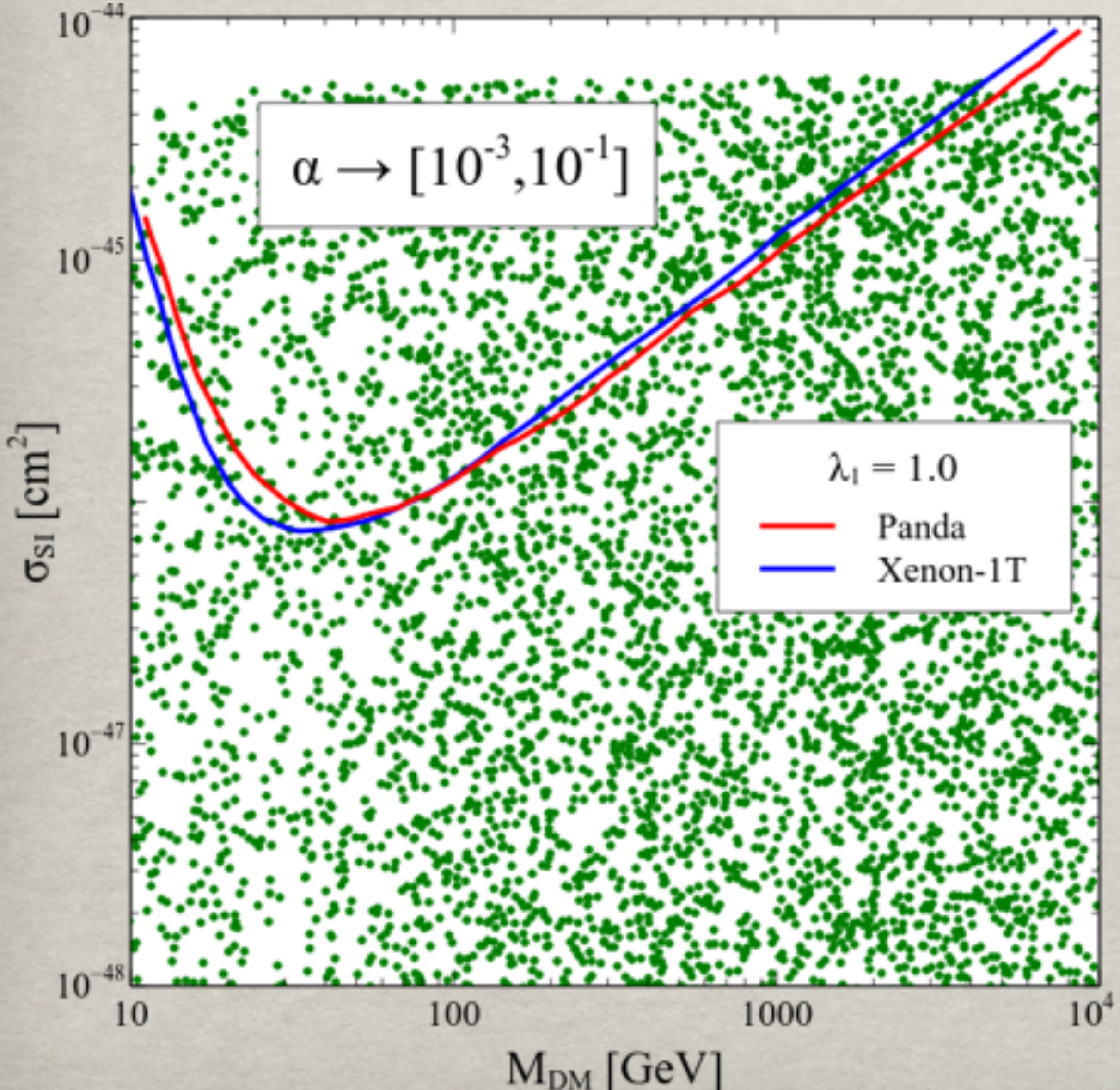
Neutrinoless $\beta\beta$ decay

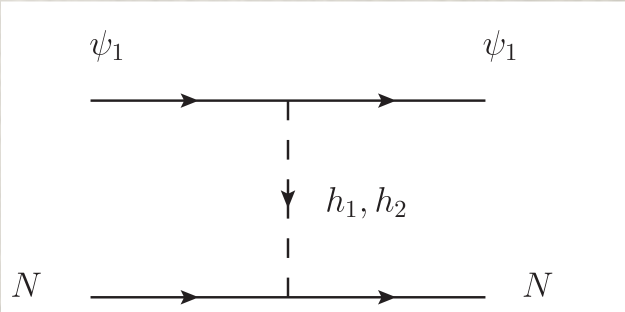
[S. Bilenki and C. Giunti 2012]



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!)

Outlook

- Does DM interact with another force apart from Gravity ? The presence of a gauge interaction for DM can have strong consequences both for its relic density and for its behaviour in structure formation at small scale… Possible to test these models !!!
- We developed a new formalism to treat the Sommerfeld enhancement at finite temperature, including screening and finite lifetime effects, and to include both scattering and bound states at the same time.
- Asymmetric Dark Matter models may possibly be able to explain the ratio of DM/baryon densities and need an efficient annihilation, possibly helped by the Sommerfeld enhancement.

Hope to detect DM interactions soon !