

# Dark matter models

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IPhU Dark Matter Day

# Past Projects: SUSY DM (Neutralinos and Charginos at $\mathcal{O}(100 \text{ GeV})$ )

D. Barducci, A. Belyaev, A. K. M. Bharucha, W. Porod and V. Sanz, JHEP 07 (2015), 066

doi:10.1007/JHEP07(2015)066 [arXiv:1504.02472 [hep-ph]], A. Bharucha, S. Heinemeyer and F. von der

Pahlen, Eur. Phys. J. C 73 (2013) no.11, 2629 doi:10.1140/epjc/s10052-013-2629-x [arXiv:1307.4237

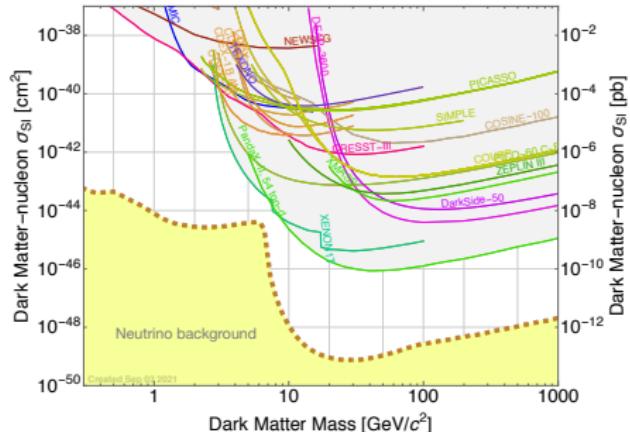
[hep-ph]], A. Bharucha, A. Fowler, G. Moortgat-Pick and G. Weiglein, JHEP 05 (2013), 053

doi:10.1007/JHEP05(2013)053 [arXiv:1211.3134 [hep-ph]], A. Bharucha, S. Heinemeyer, F. von der Pahlen and

C. Schappacher, Phys. Rev. D 86 (2012), 075023 doi:10.1103/PhysRevD.86.075023 [arXiv:1208.4106

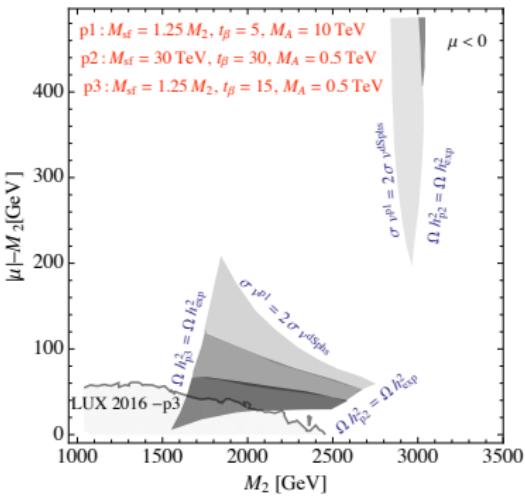
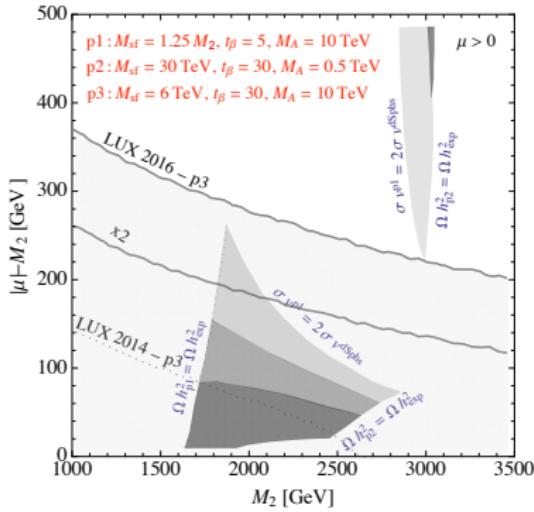
[hep-ph]].., A. Bharucha, J. Kalinowski, G. Moortgat-Pick, K. Rolbiecki and G. Weiglein, [arXiv:1208.1521

[hep-ph]].



# Past Projects: Evading the Direct Detection limits

- Nuplets (SU(2) charged multiplets): A. Bharucha, F. Brümmer and N. Desai, JHEP 11 (2018), 195 doi:10.1007/JHEP11(2018)195 [arXiv:1804.02357 [hep-ph]], A. Bharucha, F. Brümmer and R. Ruffault, JHEP 09 (2017), 160 doi:10.1007/JHEP09(2017)160 [arXiv:1703.00370 [hep-ph]].
- Heavy SUSY DM (Neutralinos and Charginos at  $\mathcal{O}(1 \text{ TeV})$ ) M. Beneke, A. Bharucha, A. Hryczuk, S. Recksiegel and P. Ruiz-Femenia, JHEP 01 (2017), 002 doi:10.1007/JHEP01(2017)002 [arXiv:1611.00804 [hep-ph]]. M. Beneke, A. Bharucha, F. Dighera, C. Hellmann, A. Hryczuk, S. Recksiegel and P. Ruiz-Femenia, JHEP 03 (2016), 119 doi:10.1007/JHEP03(2016)119 [arXiv:1601.04718 [hep-ph]]. PUBLIC CODE TO APPEAR IMMINENTLY

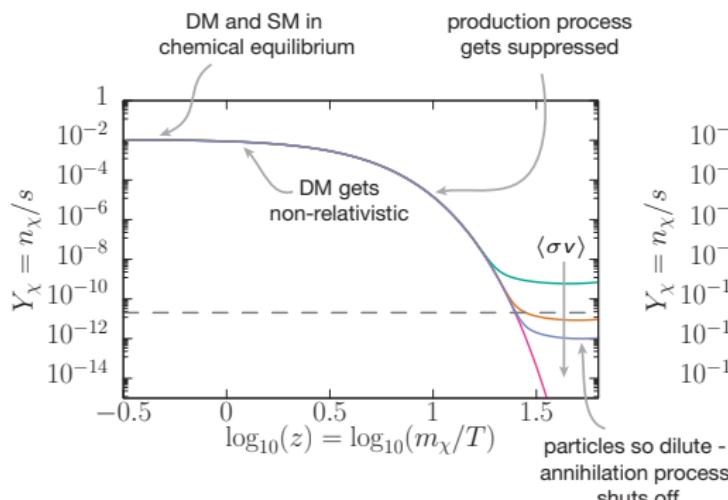


# Current Projects: Alternative DM Genesis Scenarios

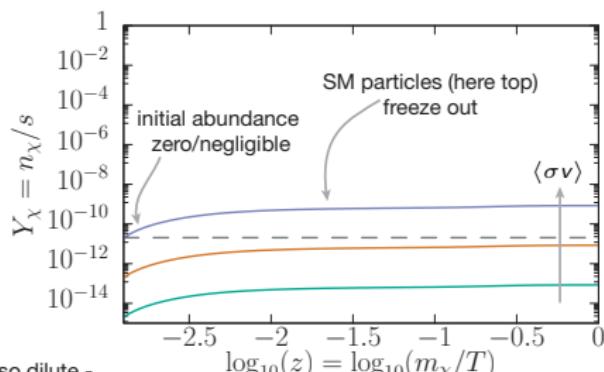
Consider simpler toy model:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \sum_f \langle \sigma_{\chi\bar{\chi} \rightarrow f\bar{f}} v \rangle (n_\chi^{\text{eq}}(T)^2 - n_\chi^2)$$

## Freeze-out



## Freeze-in



Unfortunately things not so simple! ALP also has a say...

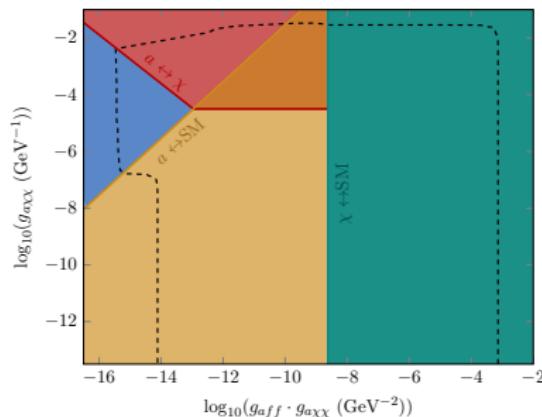
The Model: Axion-like particle ( $a$ ) mediator between the SM fermions ( $f$ ) and the DM ( $\chi$ ), a Dirac fermion

Do not consider coupling to gauge bosons at tree-level but can couple via loops, e.g.

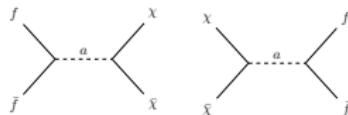
Lagrangian:

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a\partial^\mu a + \bar{\chi}(i\not{\partial} - m_\chi)\chi - \frac{1}{2}m_a^2 a^2 + ia \sum_f \frac{m_f}{f_a} C_f \bar{f} \gamma_5 f + ia \frac{m_\chi}{f_a} C_\chi \bar{\chi} \gamma_5 \chi$$

$g_{a\chi\chi} \equiv C_\chi/f_a$  (hidden sector coupling),  $g_{aff} \equiv C_f/f_a$  (connector coupling)

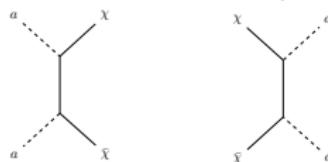


# Coupled Boltzmann equations



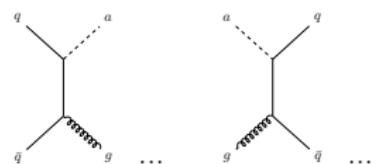
$$\frac{dn_\chi}{dt} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar{\chi} \rightarrow f\bar{f}} v \right\rangle \left( \overbrace{(n_\chi^{\text{eq}}(T))^2}^{} - \overbrace{n_\chi^2}^{} \right)$$

$$+ \underbrace{\left\langle \sigma_{aa \rightarrow \chi\bar{\chi}} v \right\rangle n_a^2}_{a \text{ dashed}} - \underbrace{\left\langle \sigma_{\chi\bar{\chi} \rightarrow aa} v \right\rangle n_\chi^2}_{\chi \text{ dashed}}$$

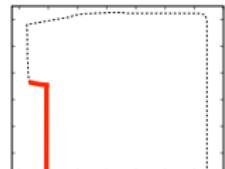
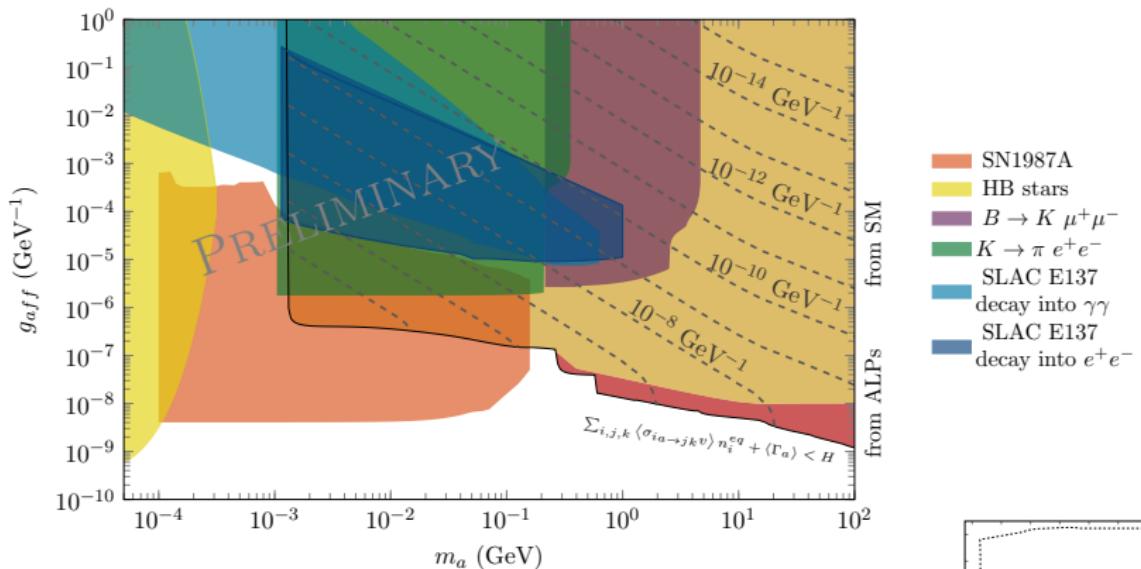


$$\frac{dn_a}{dt} + 3Hn_a = - \underbrace{\left\langle \sigma_{aa \rightarrow \chi\bar{\chi}} v \right\rangle n_a^2}_{a \text{ dashed}} + \underbrace{\left\langle \sigma_{\chi\bar{\chi} \rightarrow aa} v \right\rangle n_\chi^2}_{\chi \text{ dashed}}$$

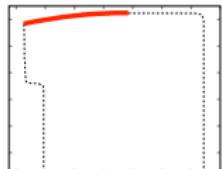
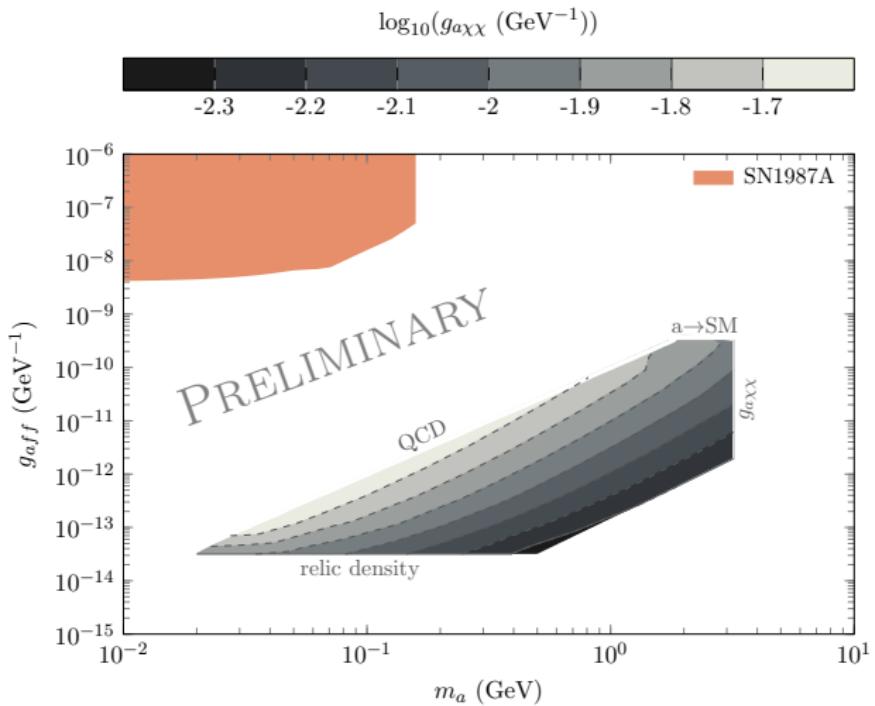
$$+ \langle \Gamma_a \rangle \left( \underbrace{n_a^{\text{eq}}(T)}_{a \text{ dashed}} - \underbrace{n_a}_{a \text{ solid}} \right) + \sum_{i,j,k} \left\langle \sigma_{ai \rightarrow jk} v \right\rangle \left( \underbrace{n_a^{\text{eq}}(T)n_i^{\text{eq}}(T)}_{a \text{ dashed}} - \underbrace{n_a n_i^{\text{eq}}(T)}_{a \text{ solid}} \right)$$



# Freeze-in vs. constraints on our ALP ( $m_\chi/m_a = 10$ )



# FODDS vs. constraints on our ALP ( $m_\chi/m_a = 10$ )



## Future Work

- Improve accuracy, in particular in sequential freeze-in region, but also in the FODDS region by solving **unintegrated Boltzmann equation**
- Assess the potential sensitivity of future experiments (**direct and indirect detection, cosmology as well as collider searches**) to the region of interest
- Study in more detail higher mass region, see if can be probed at LHC via bbar final states **IPhU/ANR project with Lorenzo Feligioni et al.**