The Relic Density *of Heavy Neutralinos*

Andrzej Hryczuk

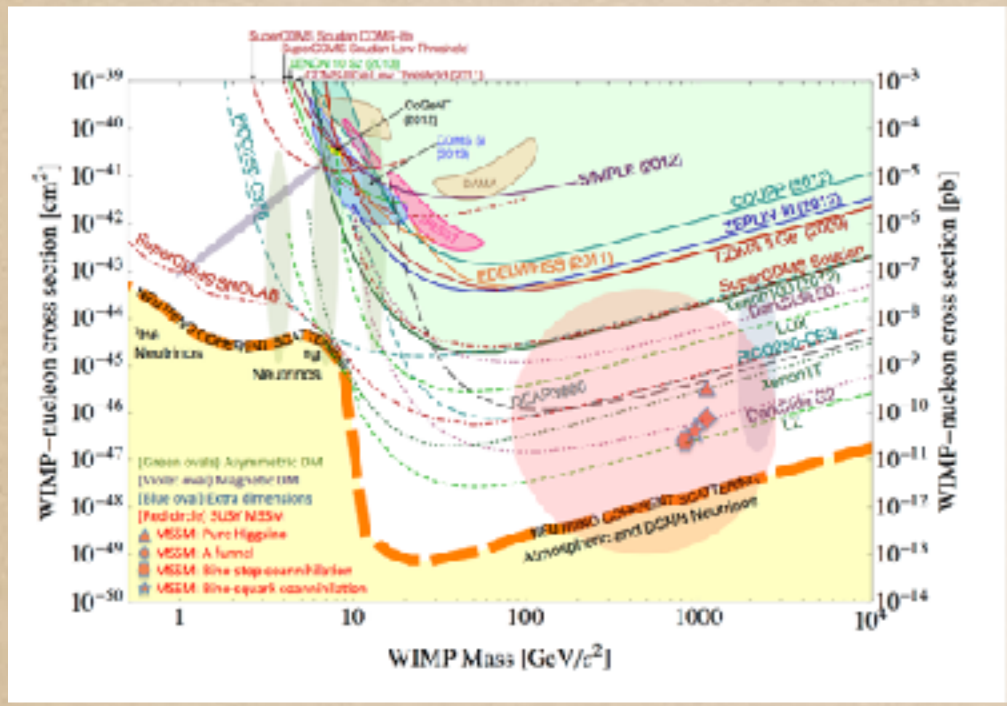
NCBJ Warsaw & *TU Munich*

in collaboration with:
Martin Beneke, Aoife Bharucha, Francesco Dighera,
Charlotte Hellmann, Stefan Recksiegel and Pedro Ruiz-Femenia

to appear soon...

Motivation

Why *heavy* neutralinos as DM?



as DD limits improve, WIMP masses $\mathcal{O}(100\,\mathrm{GeV})$ less likely

no sign of new physics at the LHC as well

+ SUSY $\Rightarrow$ neutralino DM "moves to" $\mathcal{O}(1\,\mathrm{TeV})$

Note: for heavy neutralinos ID challenging but can be very relevant

see talk of **E. Sessolo**

Motivation

Why compute relic density with high precision?

$$\Omega_{\mathrm{CDM}} h^2 = 0.1188 \pm 0.0010$$

Planck + lensing + BAO, '15

$$\Downarrow$$

uncertainty $< 1\%^*$

* does not change much when varying experimantal data combinations

widely used codes e.g. DarkSUSY, micrOMEGAs have comparable (if not slightly worse) numerical precision

theoretical uncertainty significantly larger! → (one-)loop corrections; non-perturbative effects: LL resummation, Sommerfeld enhancement (SE)

Goal: calculate relic density with SE in the full MSSM

THE SOMMERFELD EFFECT

one-loop $\propto \alpha \dfrac{m_\chi}{m_\phi}$

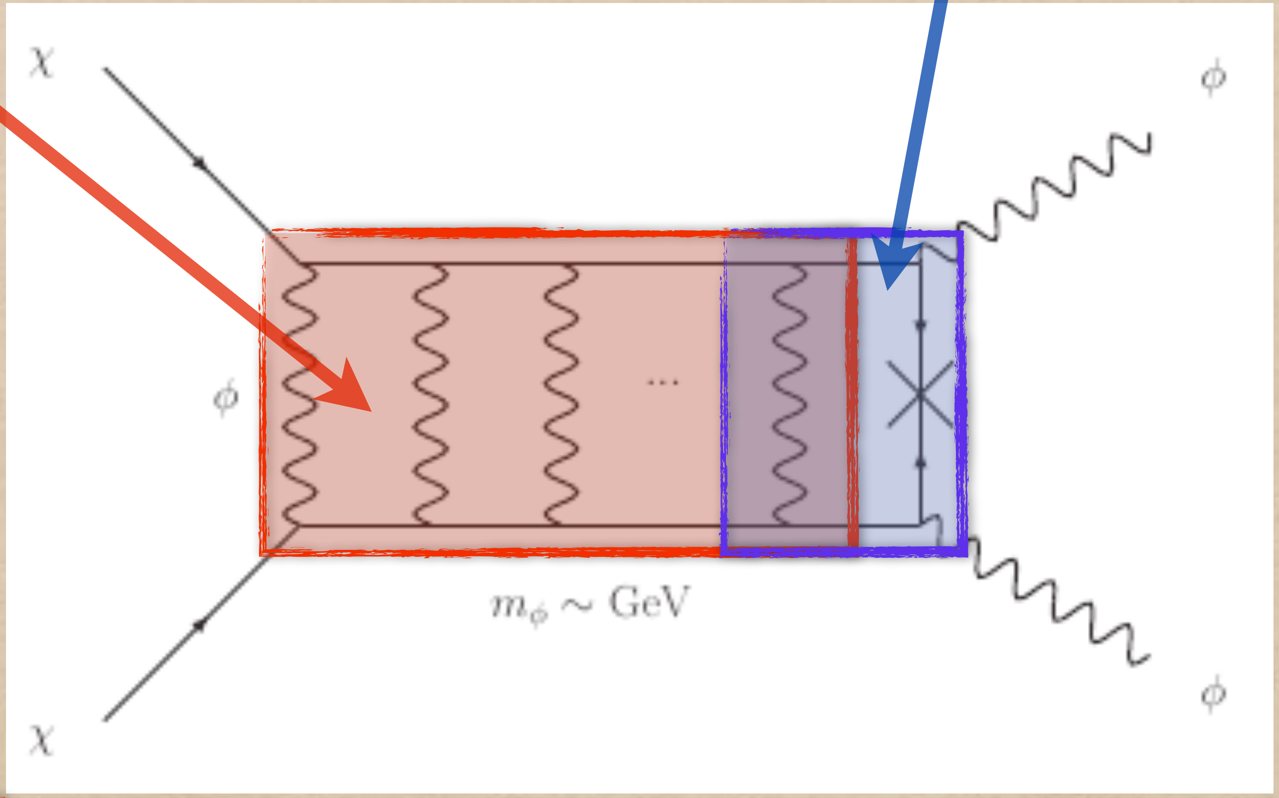
re-summation

$$\frac{1}{m_\phi} \gtrsim \frac{1}{\alpha m_\chi}$$

force range　　Bohr radius

$$m_\chi v^2 \lesssim \alpha^2 m_\chi$$

kinetic energy　　Bohr energy



$$\sigma_{\rm SE} = S(v)\,\sigma_0$$

Arkani-Hamed *et al.* '09

→ in a special case of Coulomb force: $S(v) = \dfrac{\pi\alpha/v}{1 - e^{-\pi\alpha/v}} \approx \pi\dfrac{\alpha}{v}$

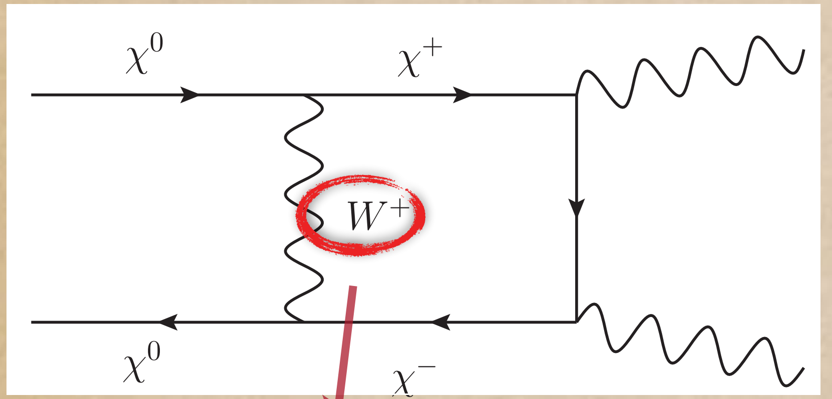
THE SOMMERFELD EFFECT
FROM EW INTERACTIONS

Hisano *et al.* '04,'06

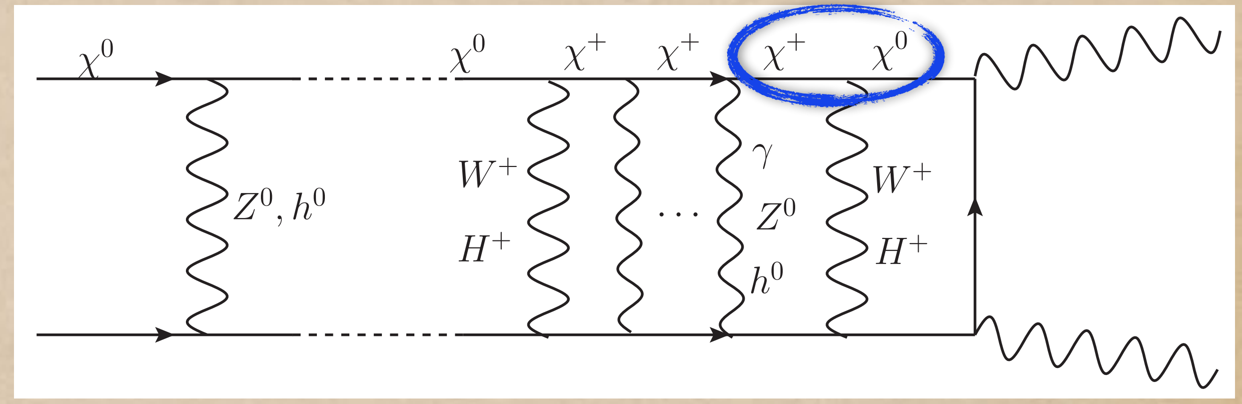
force carriers in the MSSM:

~~γ~~, $W^{\pm}$, Z^0, h^0_1, h^0_2, $H^{\pm}$

$\delta m \ll m_\chi$



$m_\chi \gg m_W$



at TeV scale $\Rightarrow$ generically effect of $\mathcal{O}(1-100\%)$

on top of that resonance structure

→ effect of $\mathcal{O}(\text{few})$
for the relic density

Note: for ID the enhancement is significantly stronger!

WHAT IS KNOWN…
WITH THE SOMMERFELD ENHANCEMENT

- pure wino, pure higgsino
  Hisano *et al*. '04,'06
- mixed wino-higgsino (with everything else decoupled)
  AH, Iengo, Ullio, '11, Beneke *et al*. '14
- stop and stau co-annihilations
  Freitas '07, **AH** '11, **Klasen** *et al*. '14
- gluino co-annihilation
  Ellis *et al*. '15
- Minimal DM model
  Cirelli *et al*. '07,'08,'09

Only available tool for the MSSM:

DarkSE package extending the relic density by SE in DarkSUSY

AH, '11

…AND WHAT WAS IMPROVED

Based on a framework by Beneke,Hellmann,Ruiz-Femenia ’12, ’13 ’14:

1. the Sommerfeld effect for P- and O(v^2) S-wave
2. off-diagonal annihilation matrices

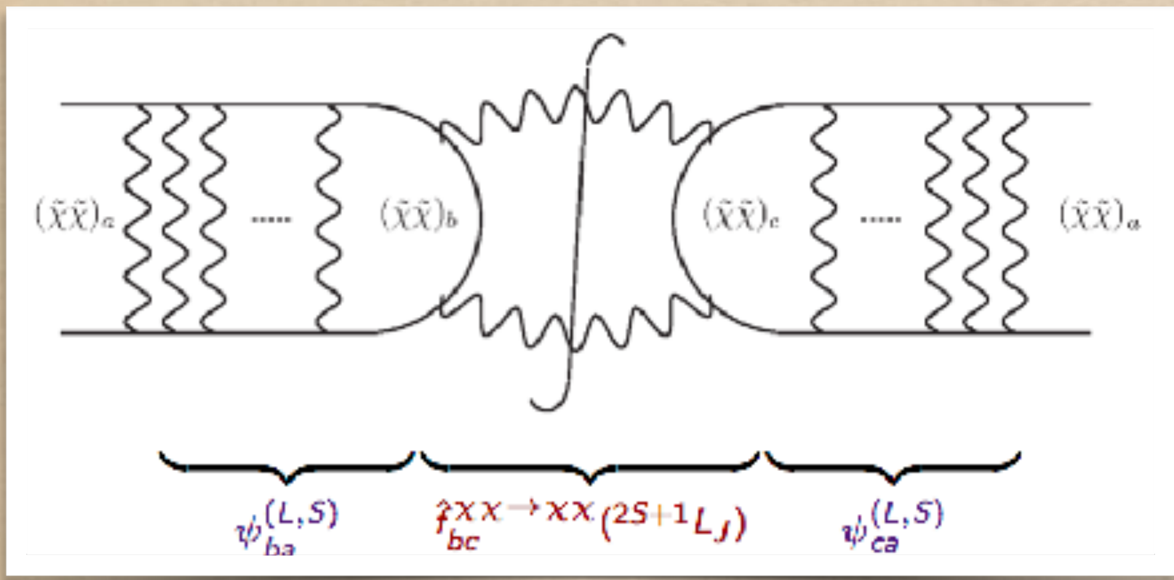
not present in DarkSE
total effect up to O(10%)

New code (to be public):

- suitable for full MSSM
- using EFT computation of annihilation matrices
- one-loop on-shell mass splittings and running couplings
- possibility of including thermal corrections
- present day annihilation in the halo (for ID)
- accuracy at O(%), dominated by theoretical uncertinities of EFT

→ caveat: still no NLO effects...

Details of the Calculation



Sommerfeld factors computed by solving Schroedinger eq. for $\psi_{ba}^{(L,S)}$

The full cross section:

$$\sigma^{(\chi\chi)_a\to\,\text{light}}\, v_{\rm rel} = S_a[\hat{f}_h(^1S_0)]\;\hat{f}_{aa}(^1S_0) + S_a[\hat{f}_h(^3S_1)]\;3\,\hat{f}_{aa}(^3S_1) + \frac{\vec{p}_a^{\,2}}{M_a^2}\Big(S_a[\hat{g}_\kappa(^1S_0)]\;\hat{g}_{aa}(^1S_0)$$
$$+\,S_a[\hat{g}_\kappa(^3S_1)]\;3\,\hat{g}_{aa}(^3S_1) + S_a\left[\frac{\hat{f}(^1P_1)}{M^2}\right]\;\hat{f}_{aa}(^1P_1) + S_a\left[\frac{\hat{f}(^3P_{\mathcal{J}})}{M^2}\right]\;\hat{f}_{aa}(^3P_{\mathcal{J}})\Big)\,,$$

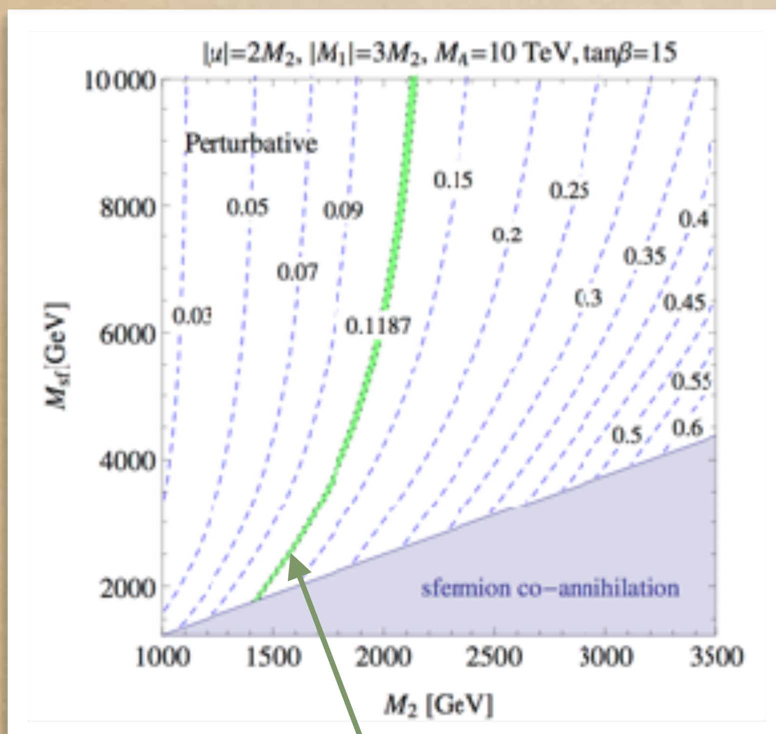
absorptive parts of the Wilson coefficients of local 4-fermion operators

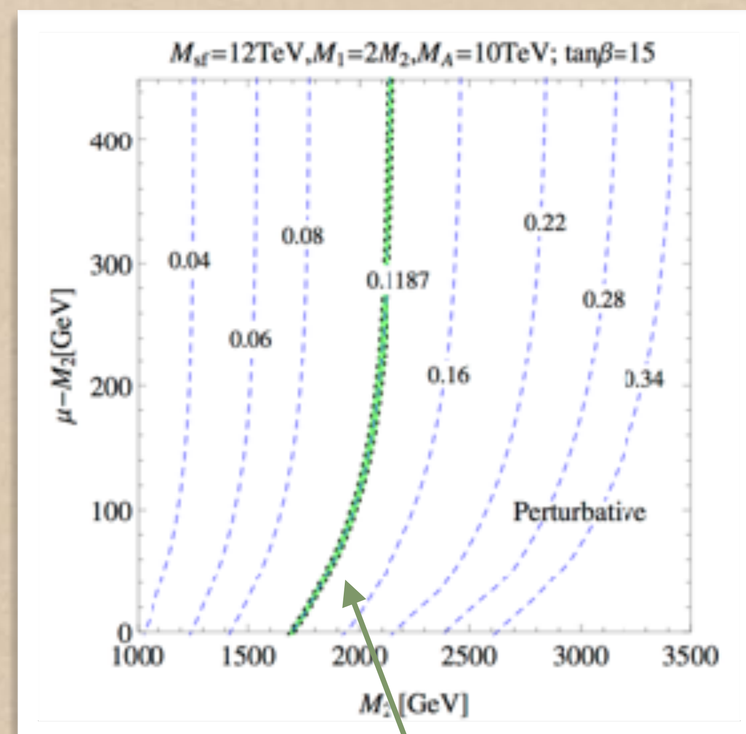
Sommerfeld factors:

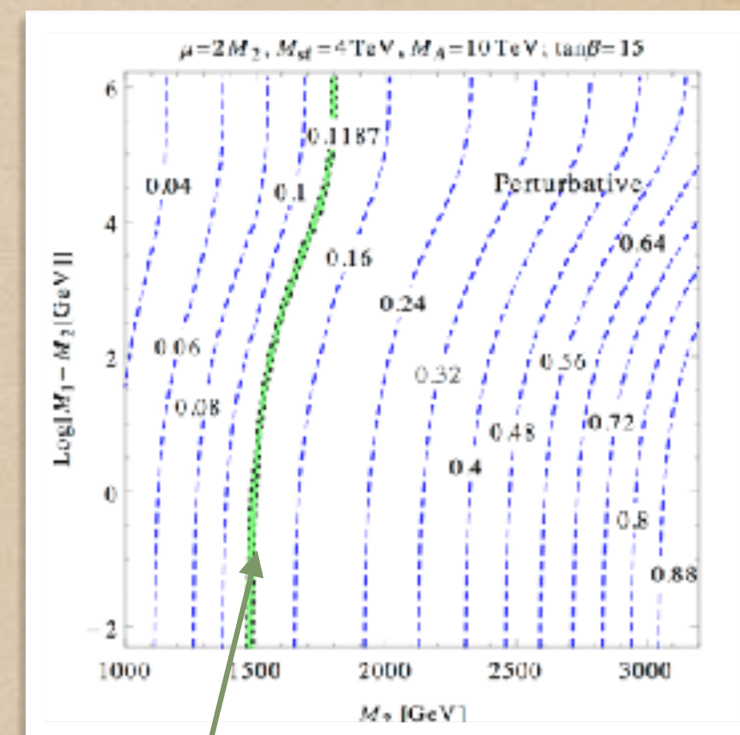
$$S_a[\hat{f}(^{2S+1}L_J)] = \frac{\left[\psi_{ca}^{(L,S)}\right]^*\,\hat{f}_{bc}^{\chi\chi\to\chi\chi}(^{2S+1}L_J)\,\psi_{ba}^{(L,S)}}{\hat{f}_{aa}^{\chi\chi\to\chi\chi}(^{2S+1}L_J)}$$

RESULTS

WINO-LIKE CASE
AT THE BORN LEVEL







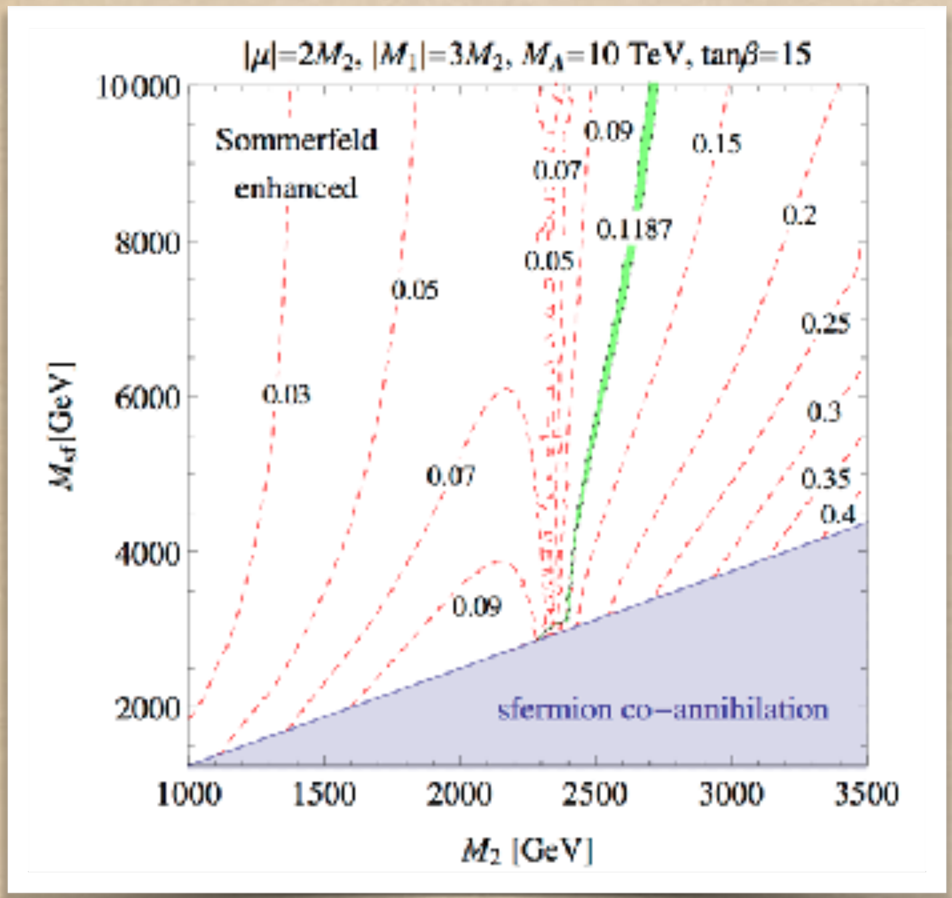
As the sfermion mass decreases the effective annihilation rate is suppressed due to t-channel interference - the correct relic abundance is obtained for masses of around 1.4 TeV*

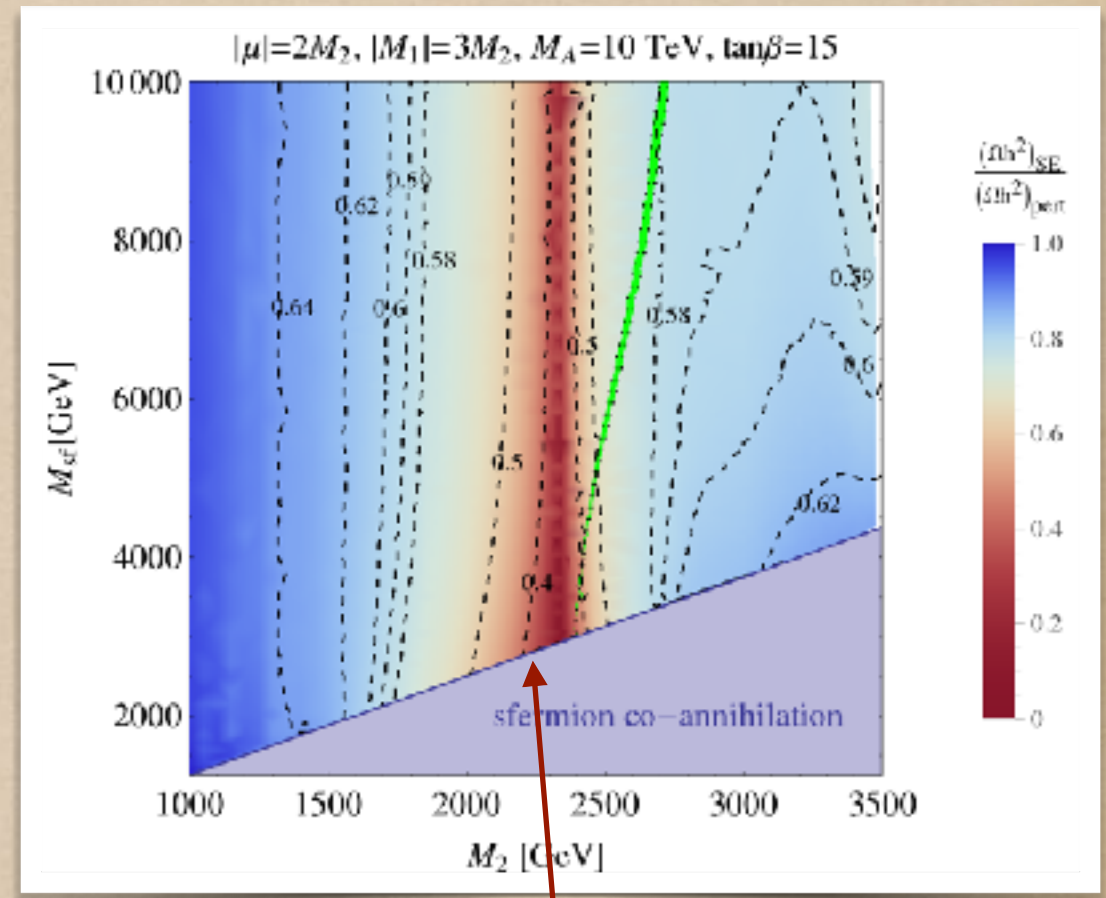
Higgsino and bino annihilate less strongly - dilute the wino annihilation and reduce the mass to 1.7 and 1.5 TeV respectively*

*for the chosen set of parameters

RESULTS

PURE WINO WITH NON-DECOUPLED SFERMIONS





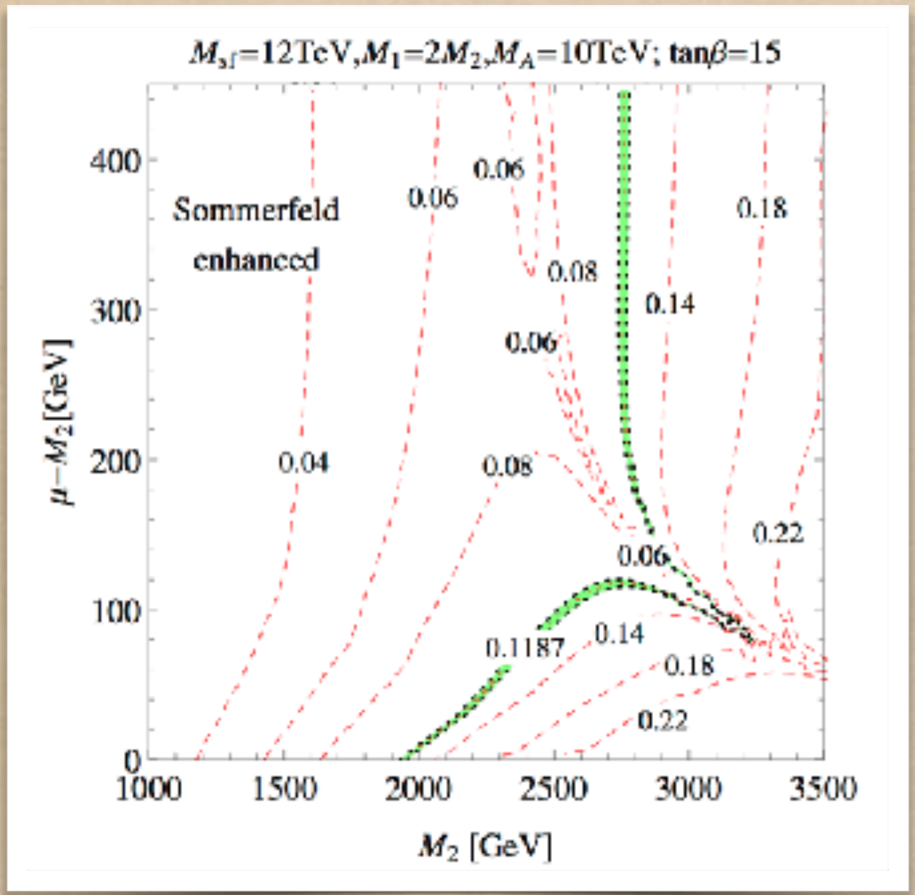
The correct relic density is moved from 1.5-2.1 TeV up to 2.4-2.8 TeV

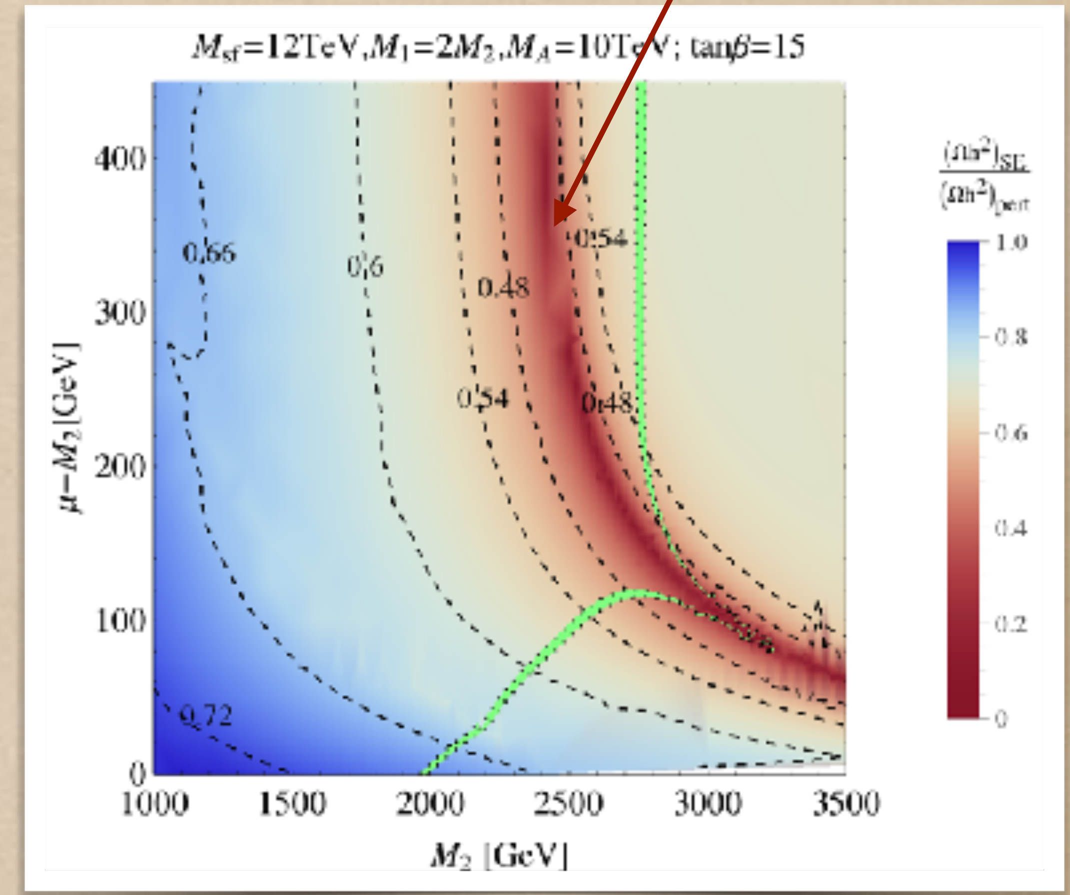
At 2.4 TeV resonance occurs, for low sfermion masses region with correct RD is resonant

RESULTS
WINO-HIGGSINO ADMIXTURE

$$\frac{1}{m_W} \simeq \frac{1}{\alpha m_\chi}$$

force range   Bohr radius



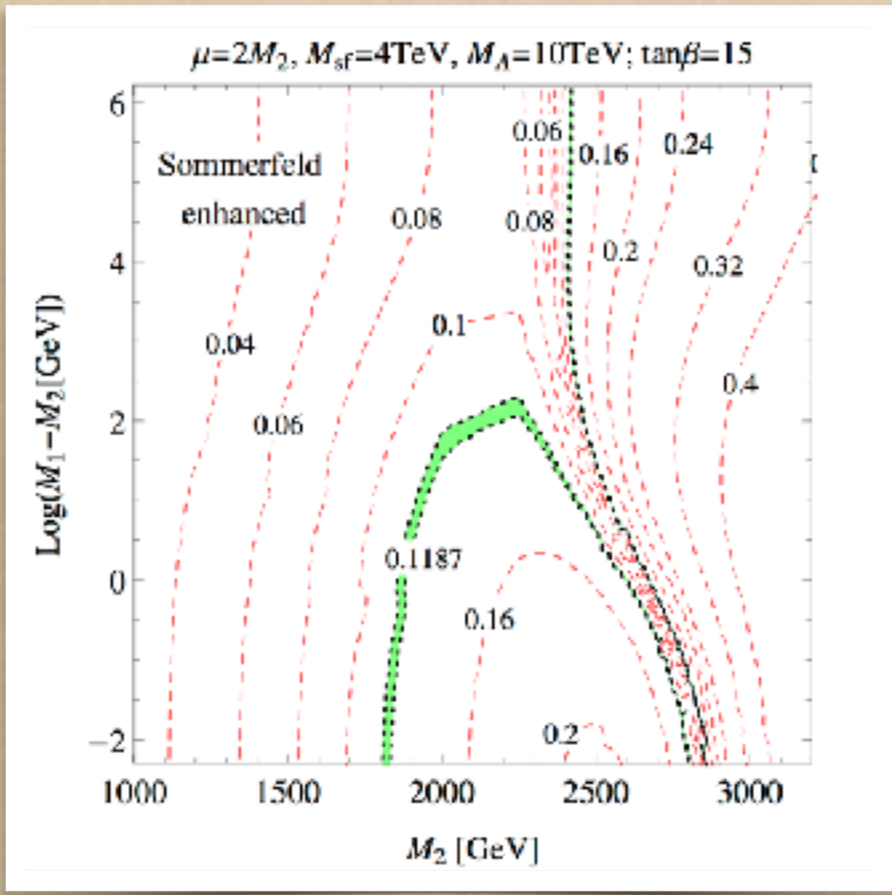


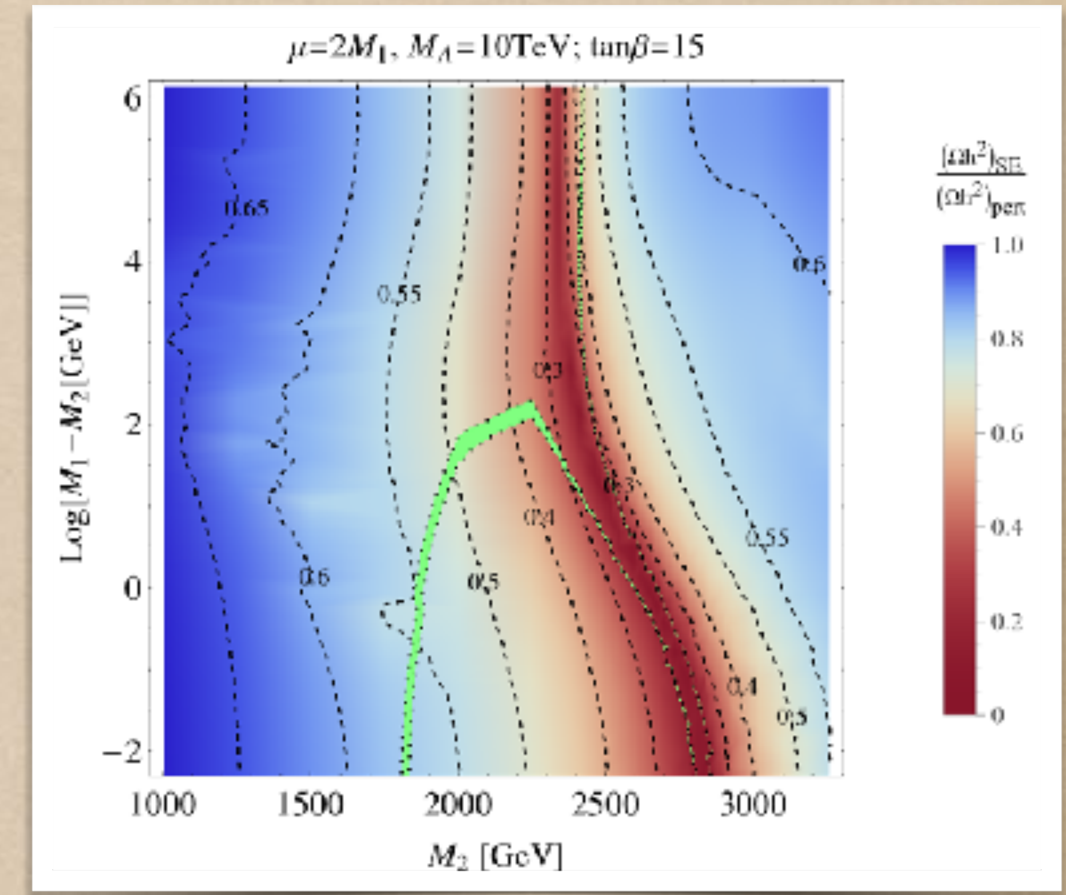
The correct relic density is moved from 1.7-2.2 TeV up to 1.9-3.3 TeV

The position of the resonance is strongly μ dependent

Results

WINO-BINO ADMIXTURE



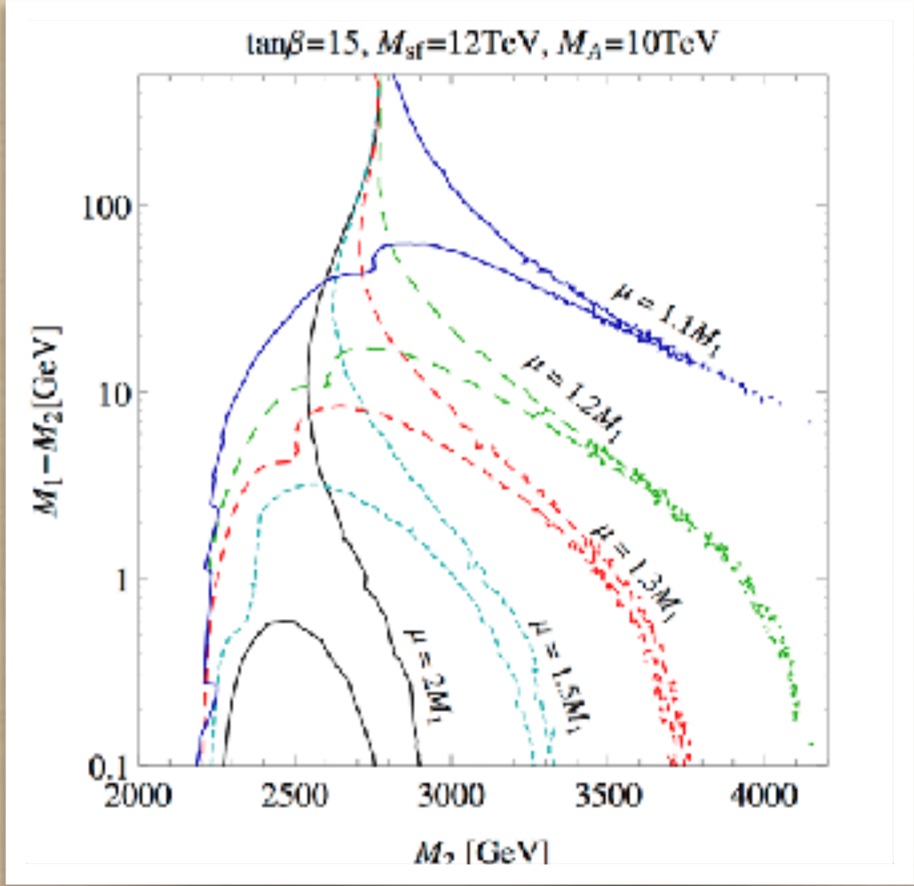


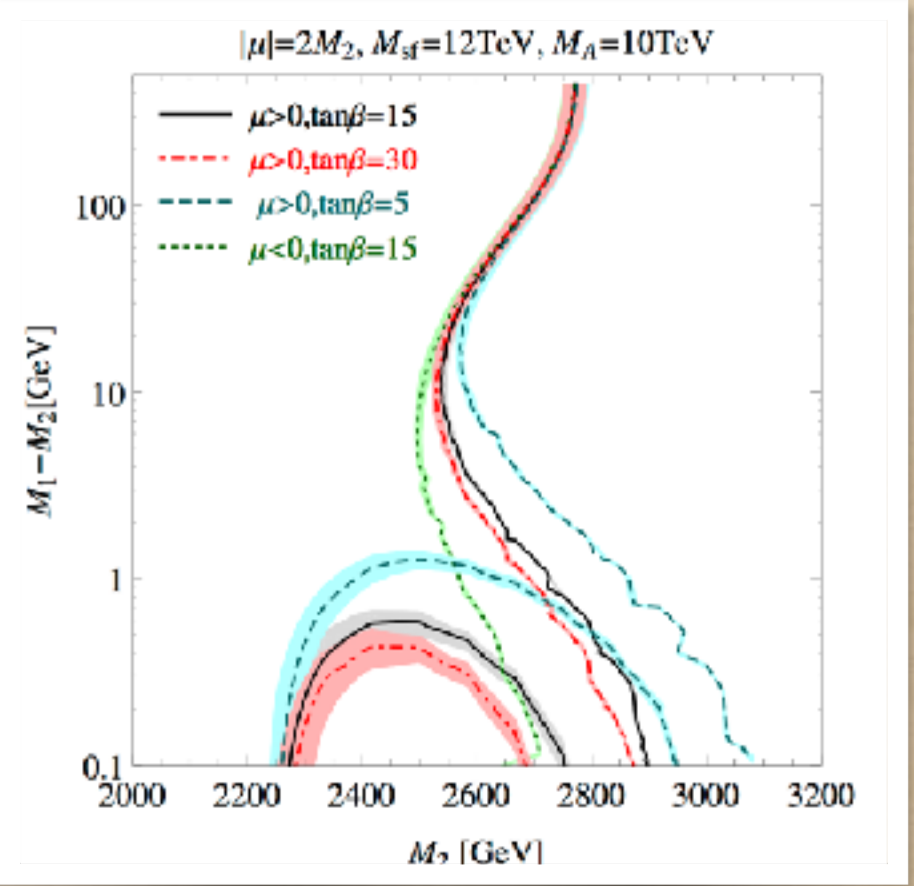
The correct relic density is moved from 1.5-1.8 TeV up to 1.8-2.9 TeV

The position of the resonance is strongly M_1 dependent

RESULTS

WINO-BINO ADMIXTURE - EFFECT OF *RESIDUAL PARAMETERS*



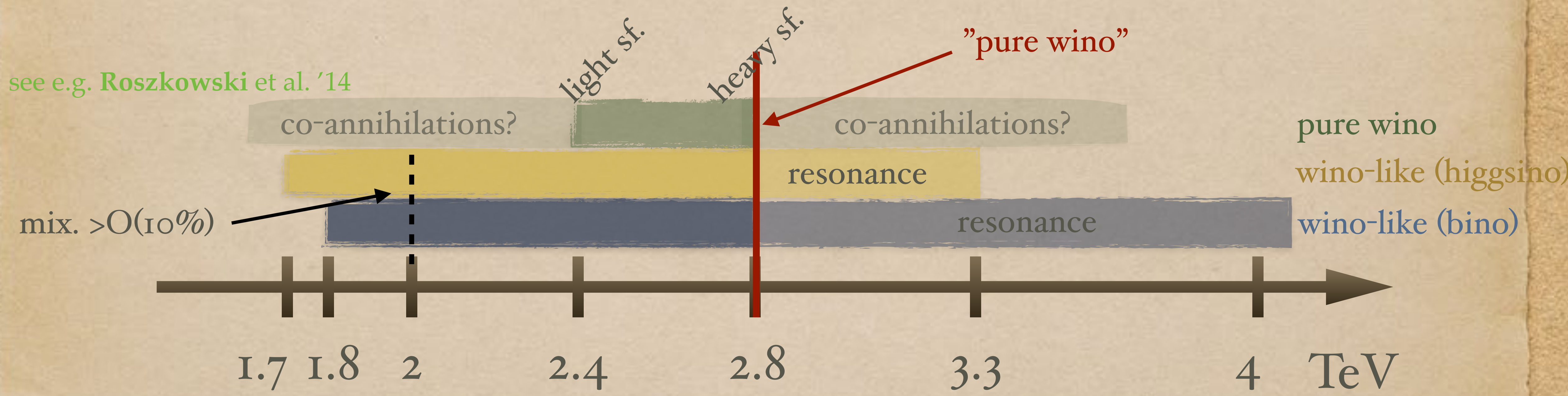


The position of the resonance is strongly dependent on choice of parameters controlling mixing, i.e. μ and $\tan\beta$

As the mixing is increased the effect is enhanced, i.e. when $|\mu|$ decreases, $\tan\beta$ decreases or μ <0

Conclusions

1. Correct relic density for wino-like neutralino in MSSM is obtained for wide range of masses:

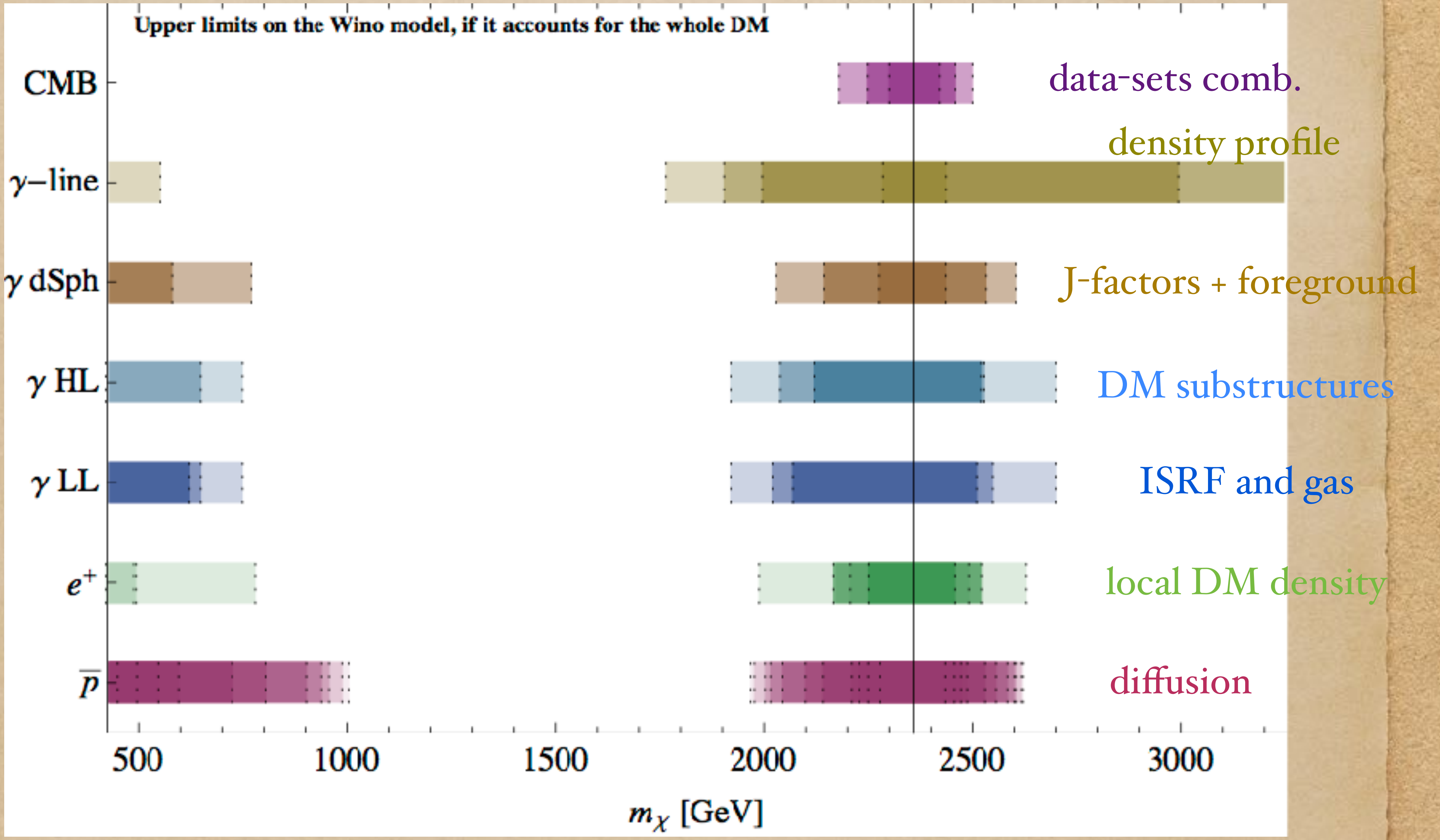


2. (Close to) resonance regions give detectable ID signals
(already constrained - work in progress...)

Public code including full SE in the MSSM with accuracy for relic density O(%) and running time O(min) to become available

Backup Slides

LIMITS ON WINO DM
UNCERTAINTIES



AH, I. Cholis, R. Iengo, M. Tavakoli, P. Ullio; JCAP 1407 (2014) 031

RELIC DENSITY
WITH THE SE

Boltzmann equation for the comoving number density;

$$\frac{dY}{dx} = \sqrt{\frac{g_* \pi m_\chi^2}{45G}} \frac{\langle \sigma_{\rm eff} \mathrm{v} \rangle}{x^2} \left(Y^2 - Y_{\rm eq}^2\right)$$

effective thermal averaged annihilation cross-section:

$$\langle \sigma_{\rm eff} \mathrm{v} \rangle = \sum_{ij} \langle \sigma_{ij} \mathrm{v}_{ij} \rangle \frac{n_i^{\rm eq} n_j^{\rm eq}}{n_{\rm eq}^2}$$

with: $\sigma_{ij} = \sum_X \sigma(\chi_i \chi_j \to X)$

$$\langle \sigma_{\rm eff} \mathrm{v} \rangle = \sum_{ij} S_{ij}(T, \mathrm{v}) \langle \sigma_{ij} \mathrm{v}_{ij} \rangle \frac{n_i^{\rm eq} n_j^{\rm eq}}{n_{\rm eq}^2}$$

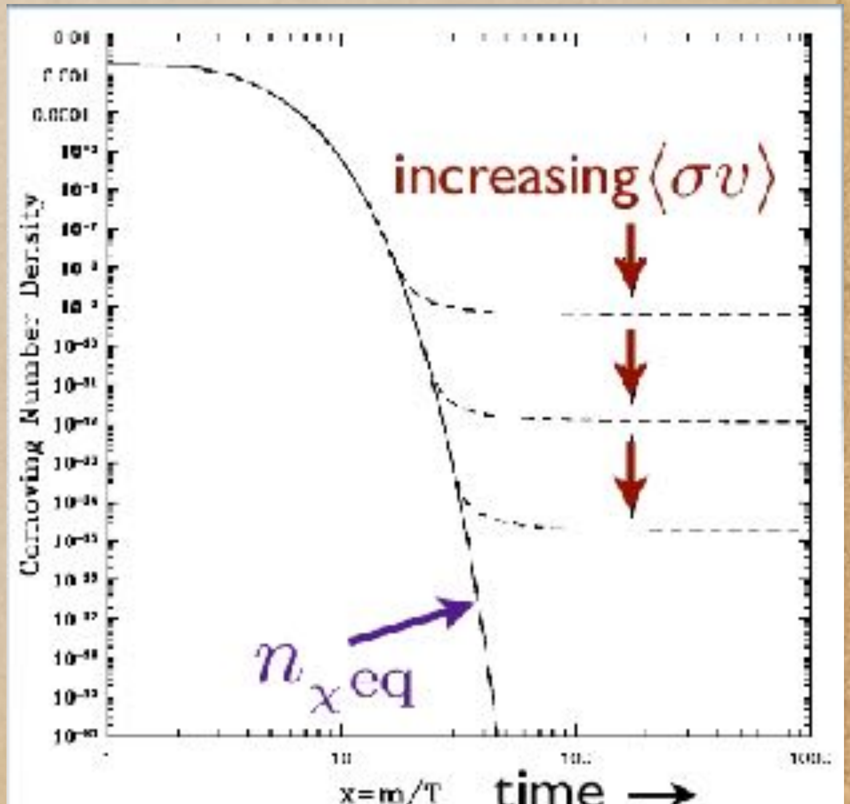


Fig.: Jungman, Kamionkowski & Griest, PR'96