# NEUTRALINO DARK MATTER AT TEV SCALE REVISITED

Andrzej Hryczuk

University of Oslo*

**based on:**

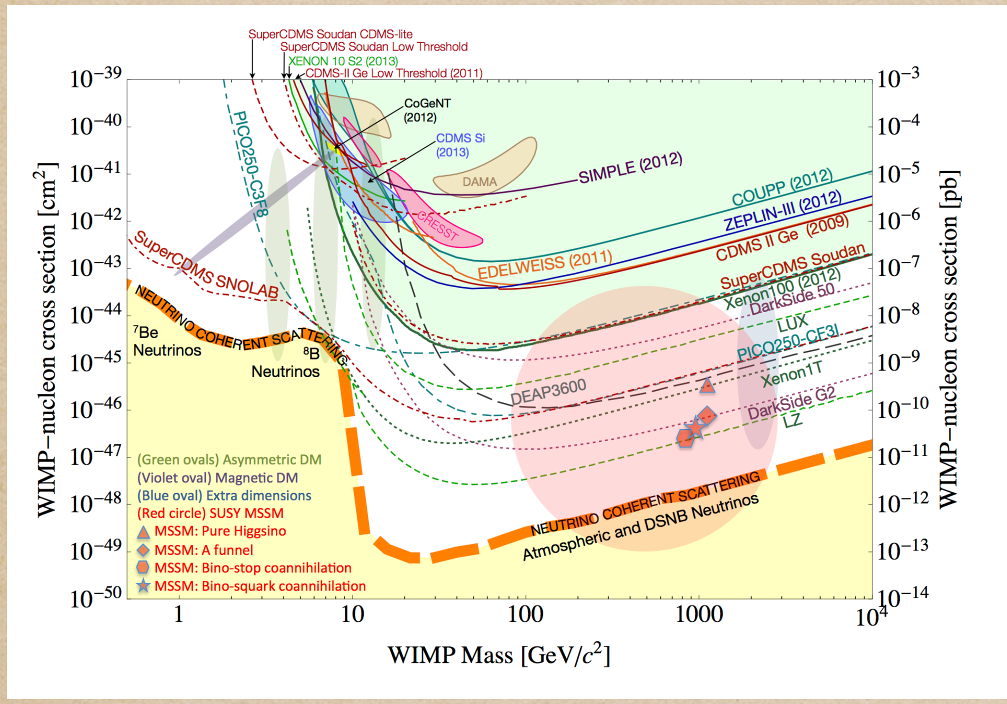
M. Beneke, A. Bharucha, F. Dighera,
C. Hellmann, AH, S. Reckiegel, P. Ruiz-Femenia; *1601.04718*

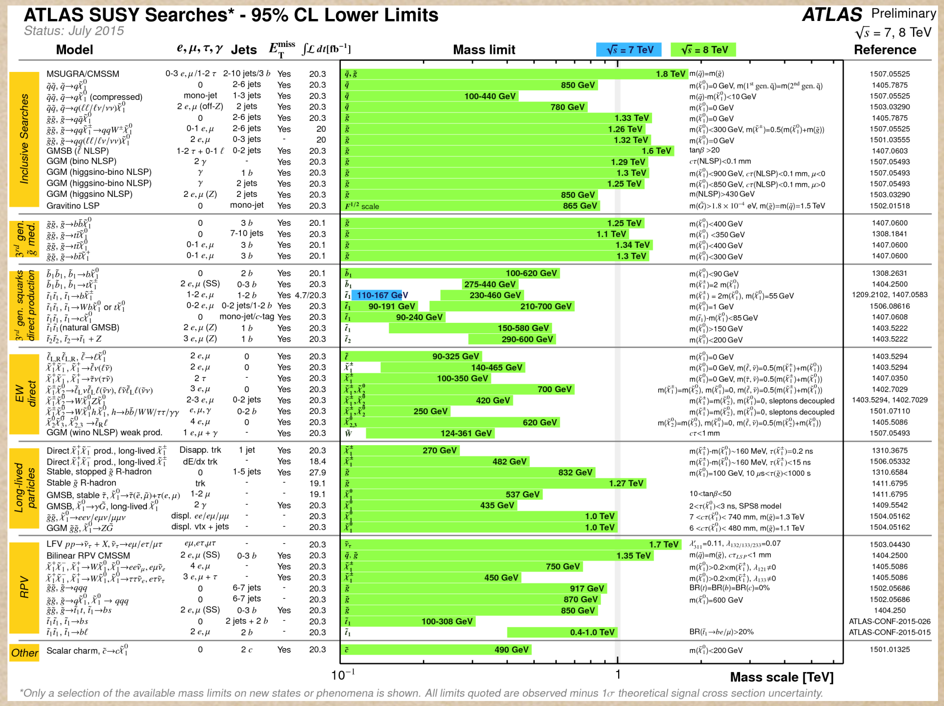
M. Beneke, A. Bharucha, AH,
S. Reckiegel, P. Ruiz-Femenia; *in prep.*

*on leave from National Centre for Nuclear Research, Warsaw, Poland

# Motivation

## Why *heavy* neutralinos as DM?




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

no sign of new physics at the LHC as well

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

$\Downarrow$

**Relic density and ID limits/prospects need to be revisited**

# 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 experimental 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 + ID signals with SE in the full MSSM

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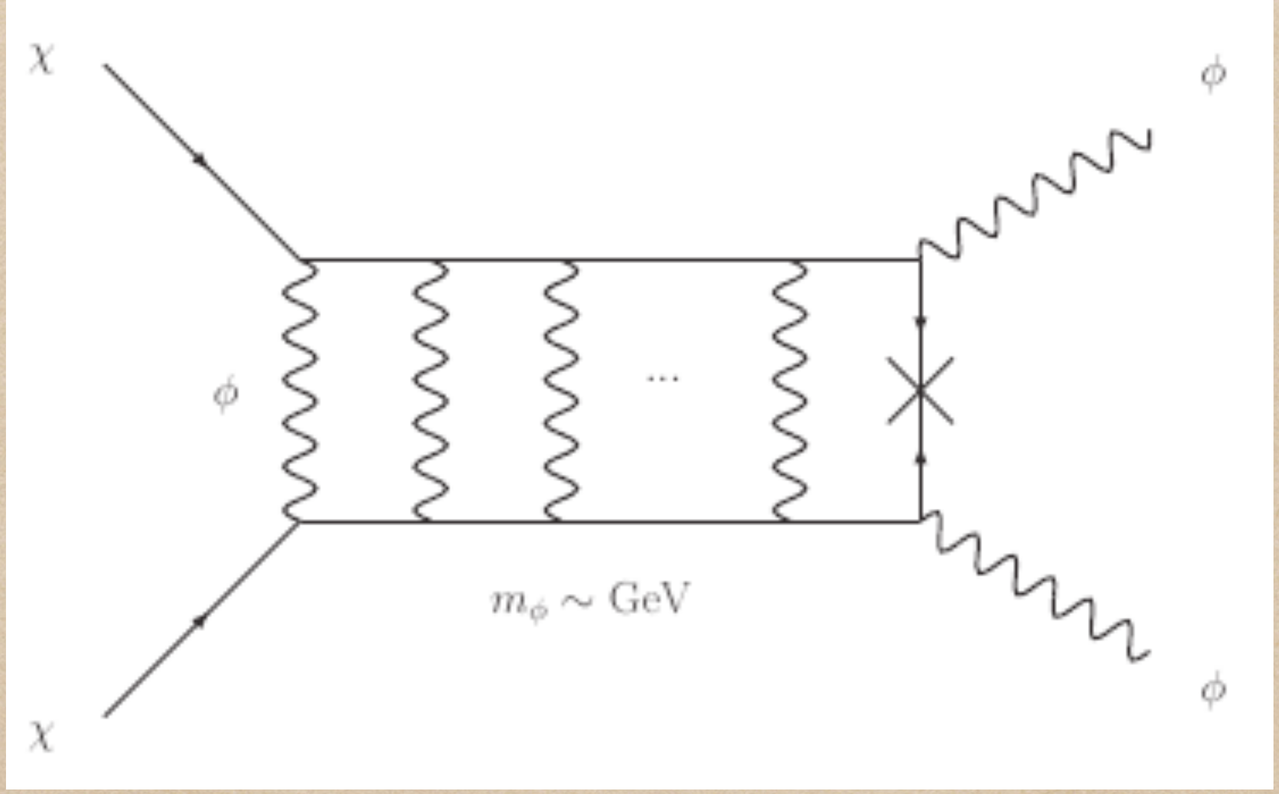
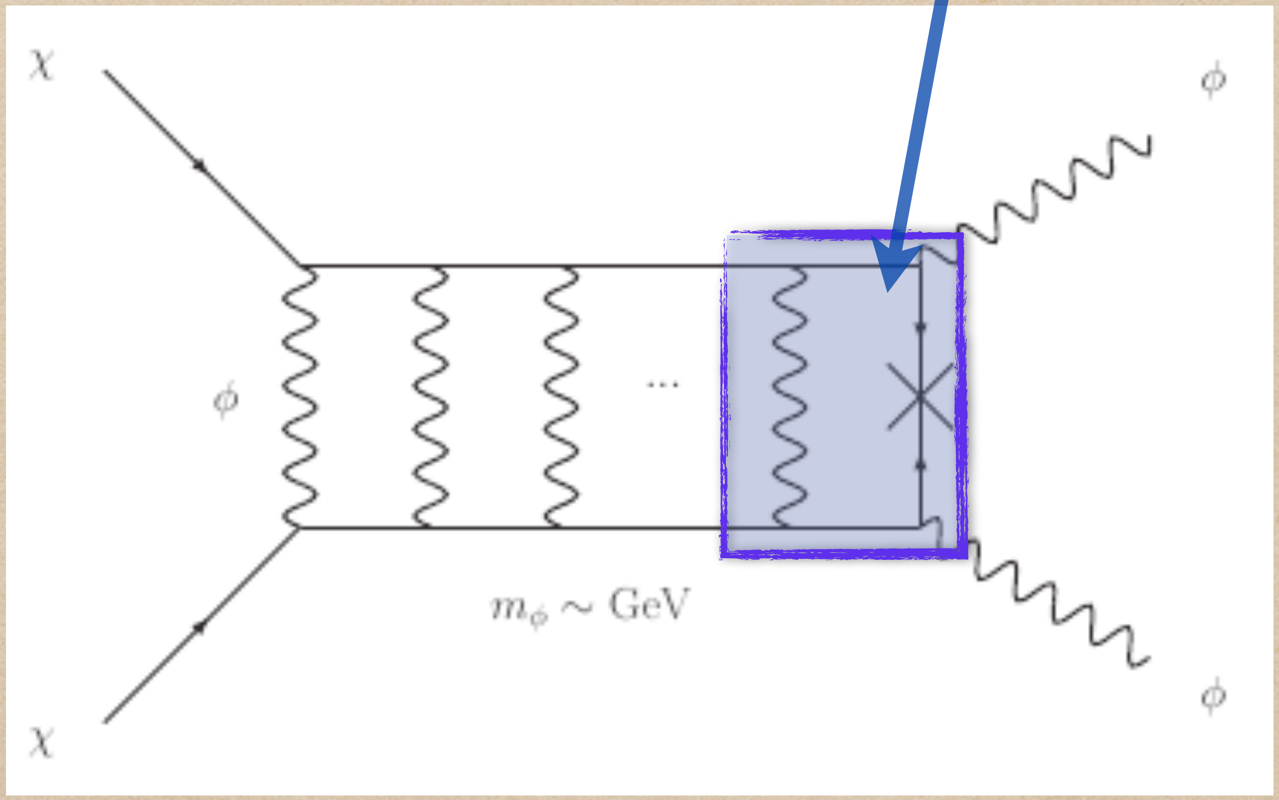
# THE SOMMERFELD EFFECT




**Arkani-Hamed *et al.* '09**

# THE SOMMERFELD EFFECT

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




Arkani-Hamed *et al.* '09

# THE SOMMERFELD EFFECT

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

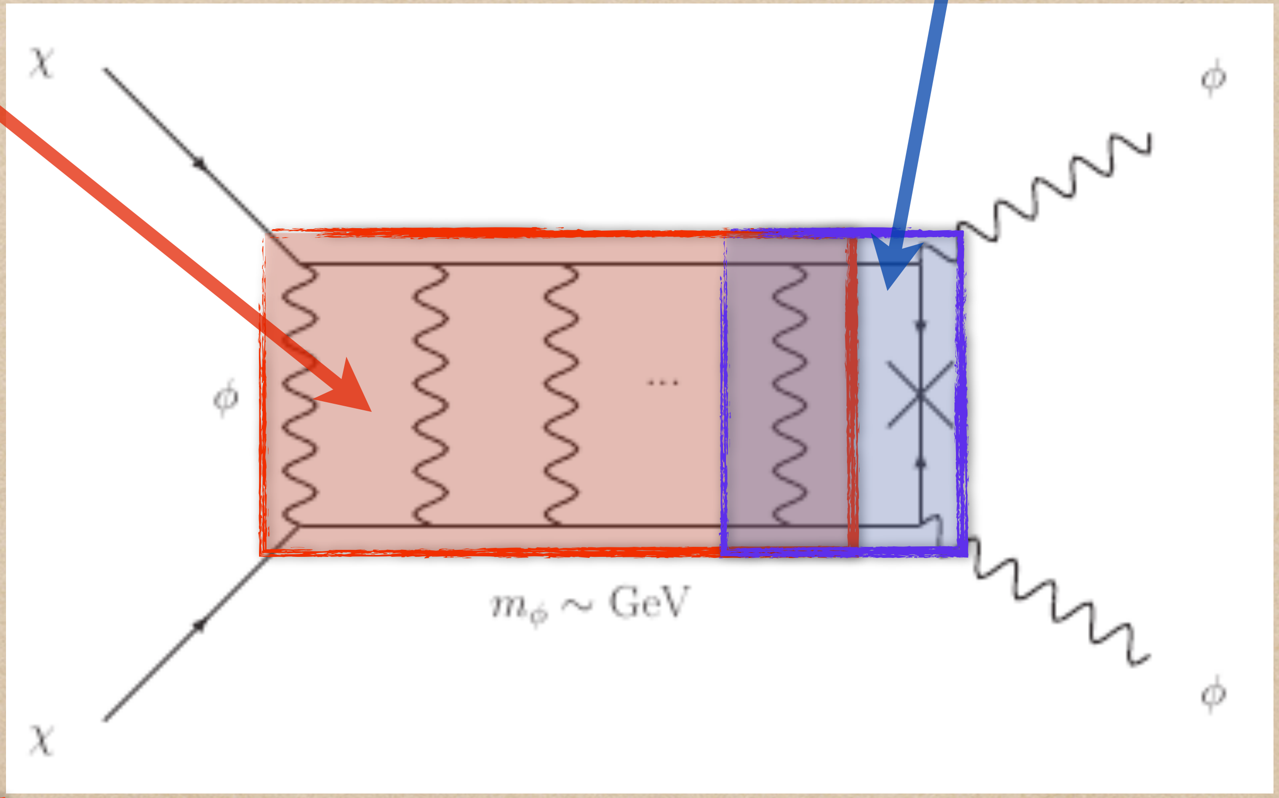
re-summation

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

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: $S(v) = \frac{\pi\alpha/v}{1 - e^{-\pi\alpha/v}} \approx \pi\frac{\alpha}{v}$

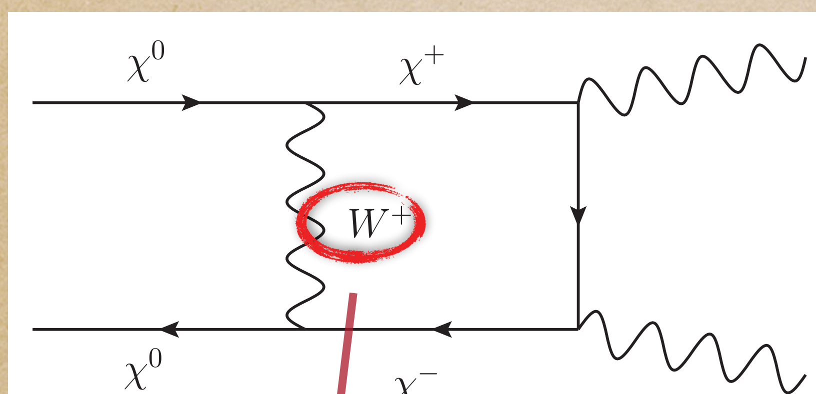
# THE SOMMERFELD EFFECT
## FROM EW INTERACTIONS

**Hisano *et al.* '04,'06**

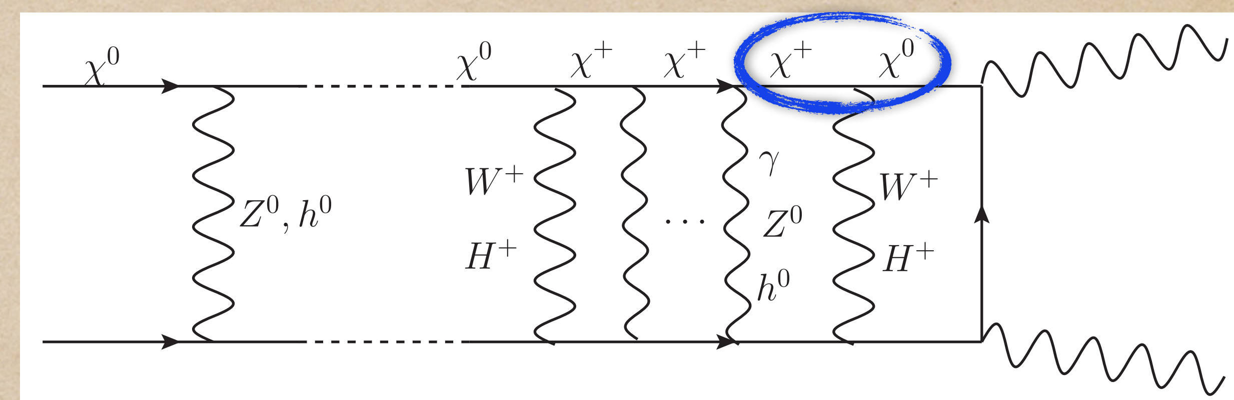
force carriers in the MSSM:

$\gamma,\ W^\pm,\ Z^0,\ h_1^0,\ h_2^0,\ H^\pm$

$\delta m \ll m_\chi$




$m_\chi \gg m_W$




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%)

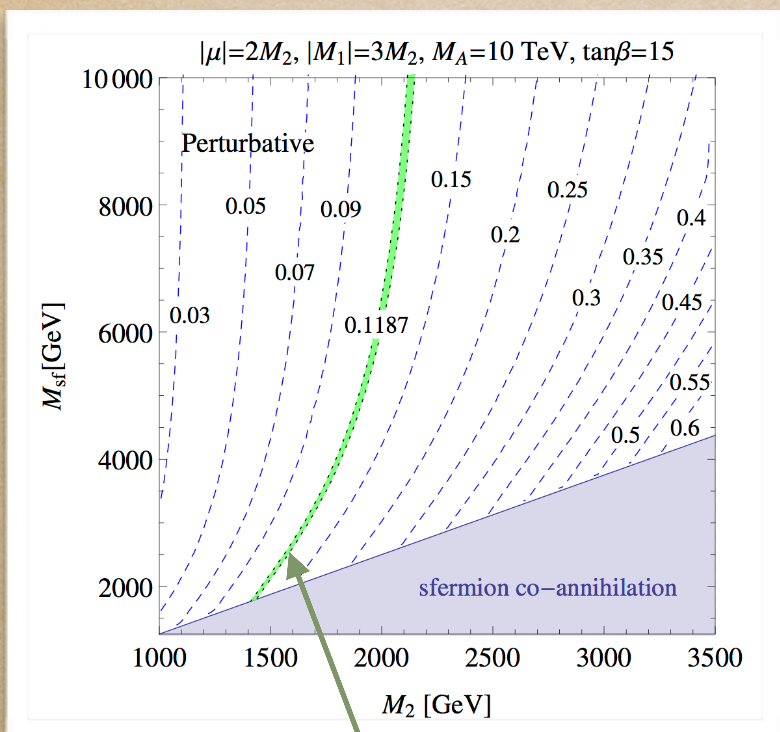
New code (to be public):

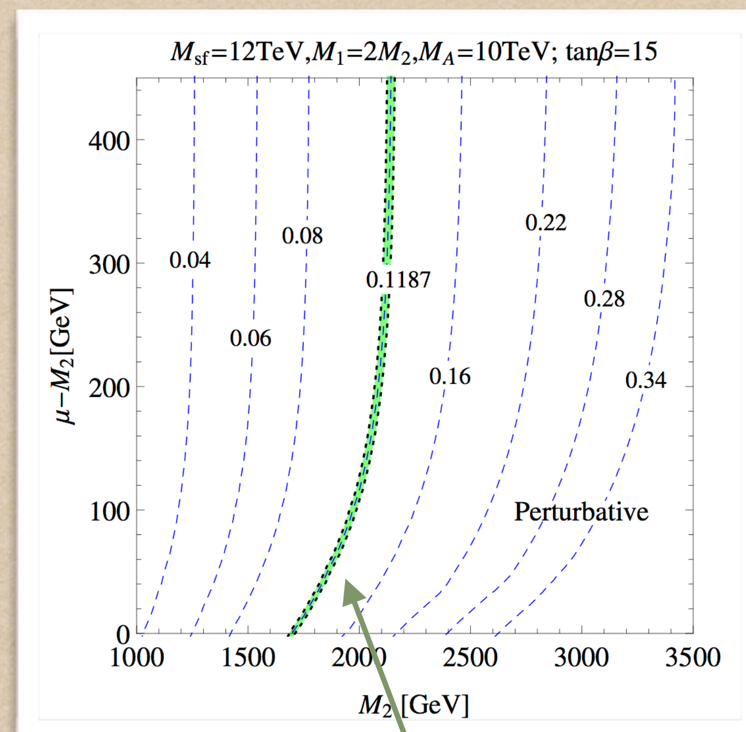
- suitable for full MSSM
- using EFT computation of annihilation matrices
- one-loop on-shell mass splittings and running couplings
- possibility of including thermal corrections
- present day annihilation in the halo (for ID)
- accuracy at O(%), dominated by theoretical uncertinities of EFT

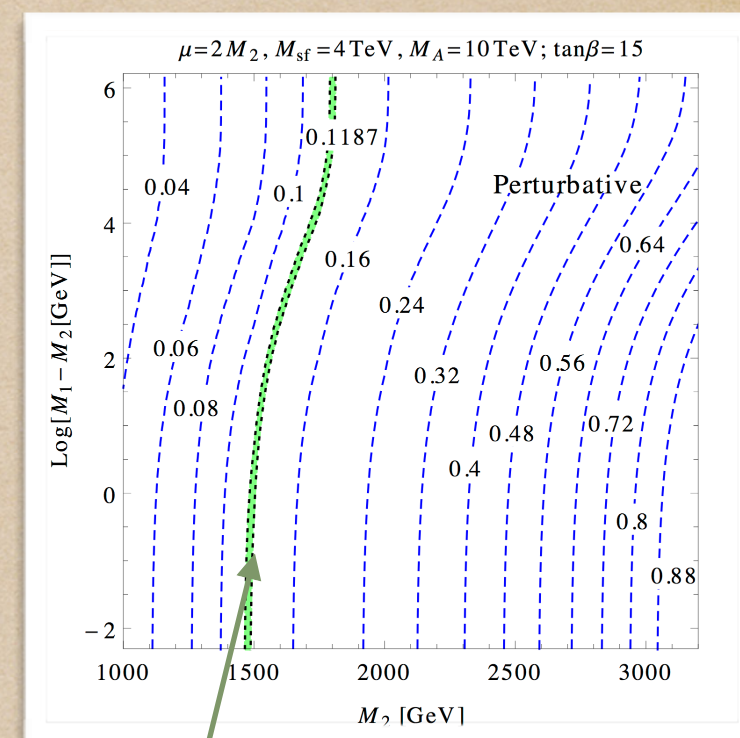
→ caveat: still no NLO effects…

# Results
## Relic Density

# WINO-LIKE CASE
## AT THE BORN LEVEL



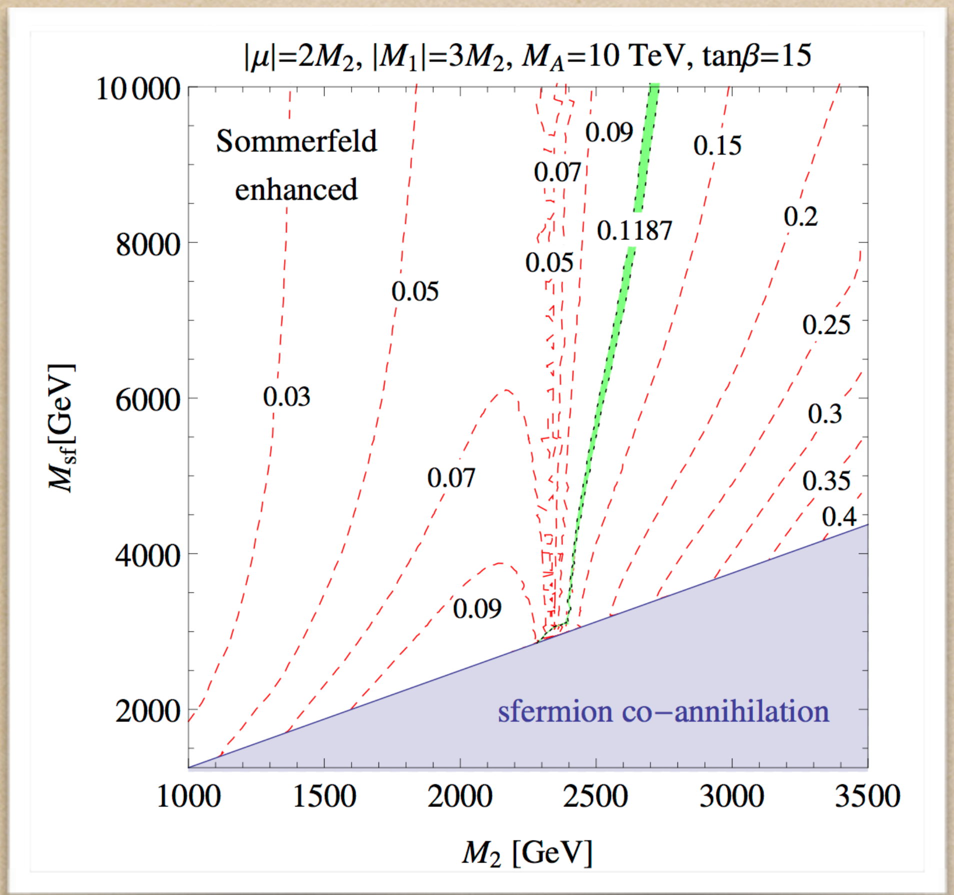

As the sfermion mass decreases the effective annihilation rate is suppressed due to t-channel interference - the correct relic abundance is obtained for masses of around 1.4 TeV*

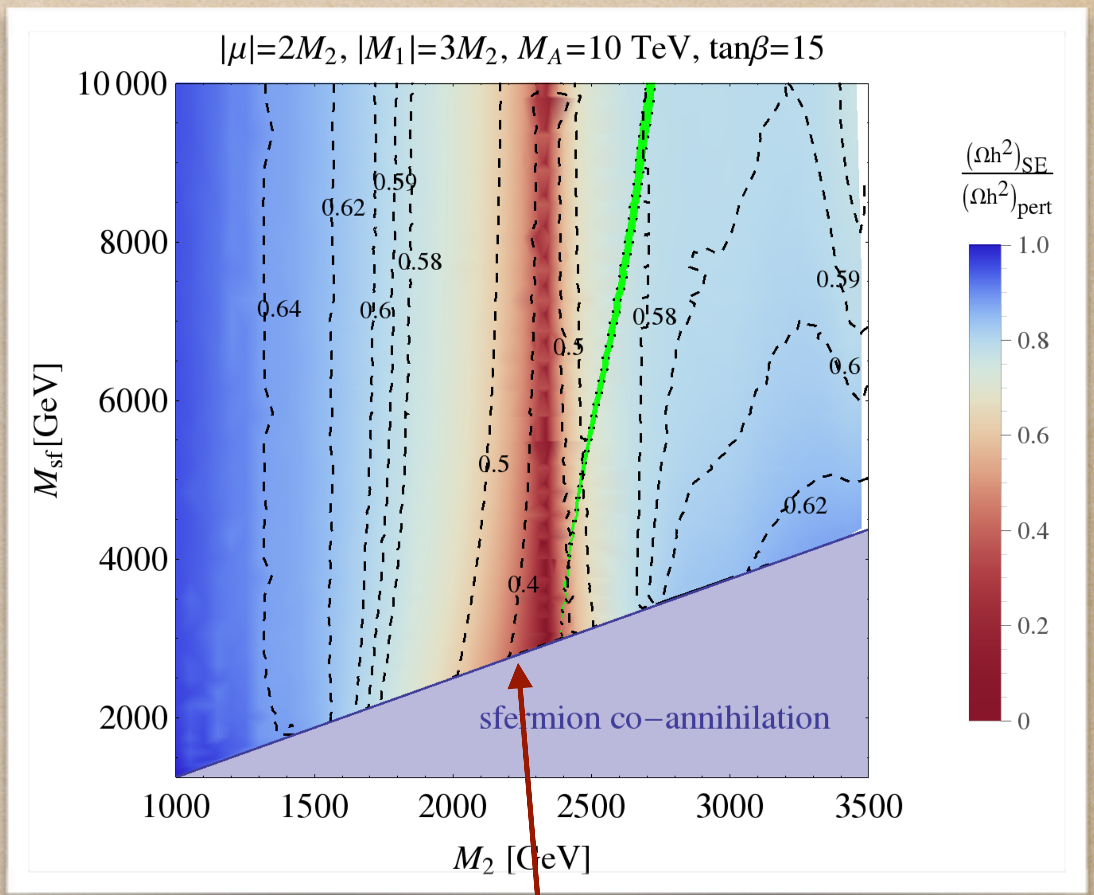
Higgsino and bino annihilate less strongly - dilute the wino annihilation and reduce the mass to 1.7 and 1.5 TeV respectively*

*for the chosen set of parameters

# RESULTS

## PURE WINO WITH NON-DECOUPLED SFERMIONS

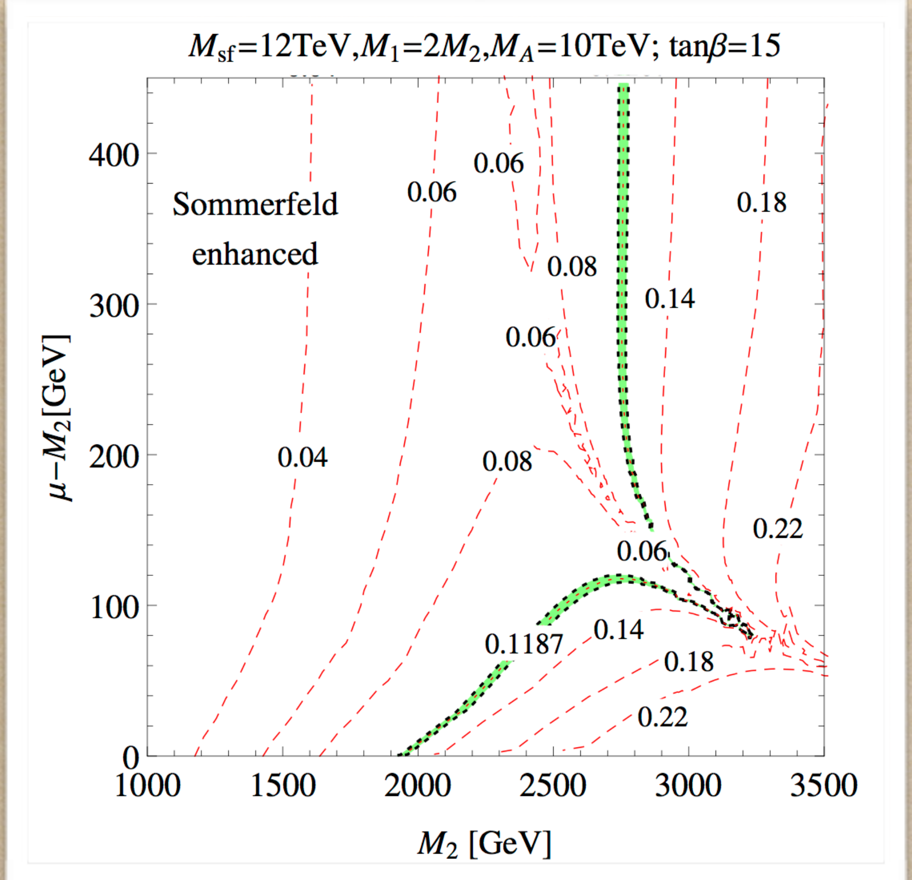


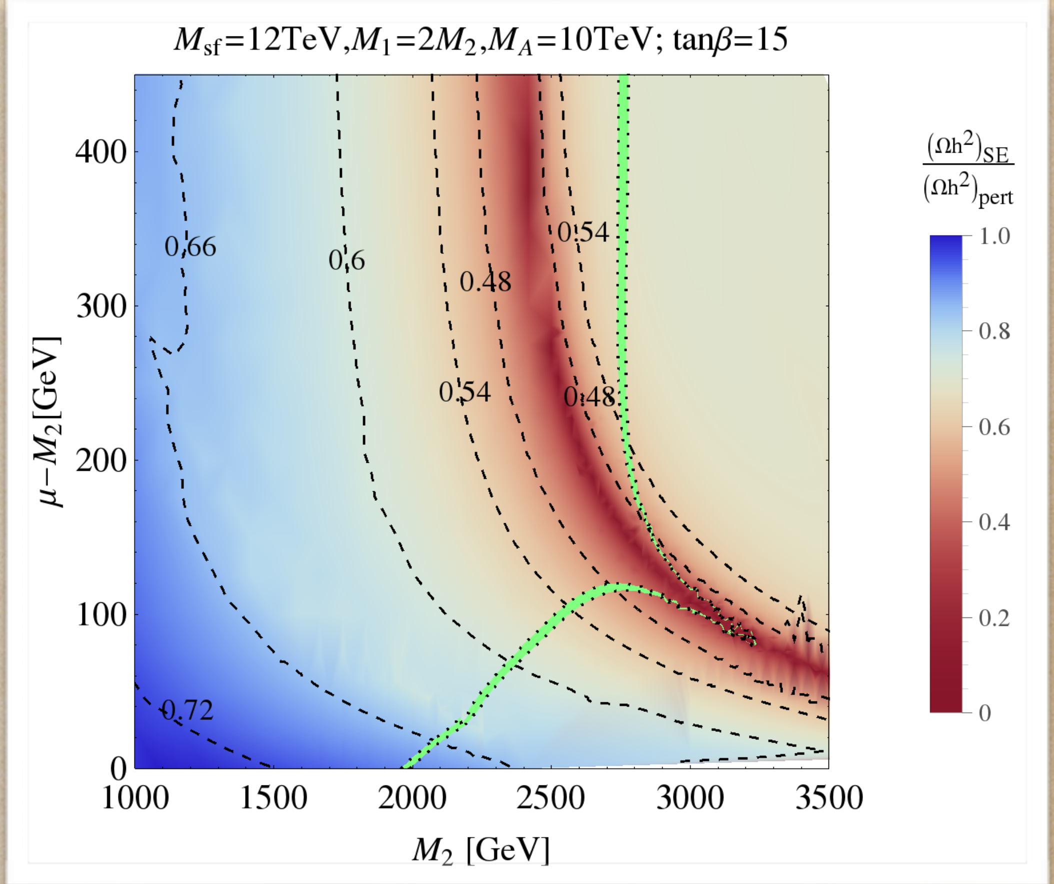




The correct relic density is moved from 1.5-2.1 TeV up to **2.4-2.8 TeV**

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

# RESULTS
## WINO-HIGGSINO ADMIXTURE



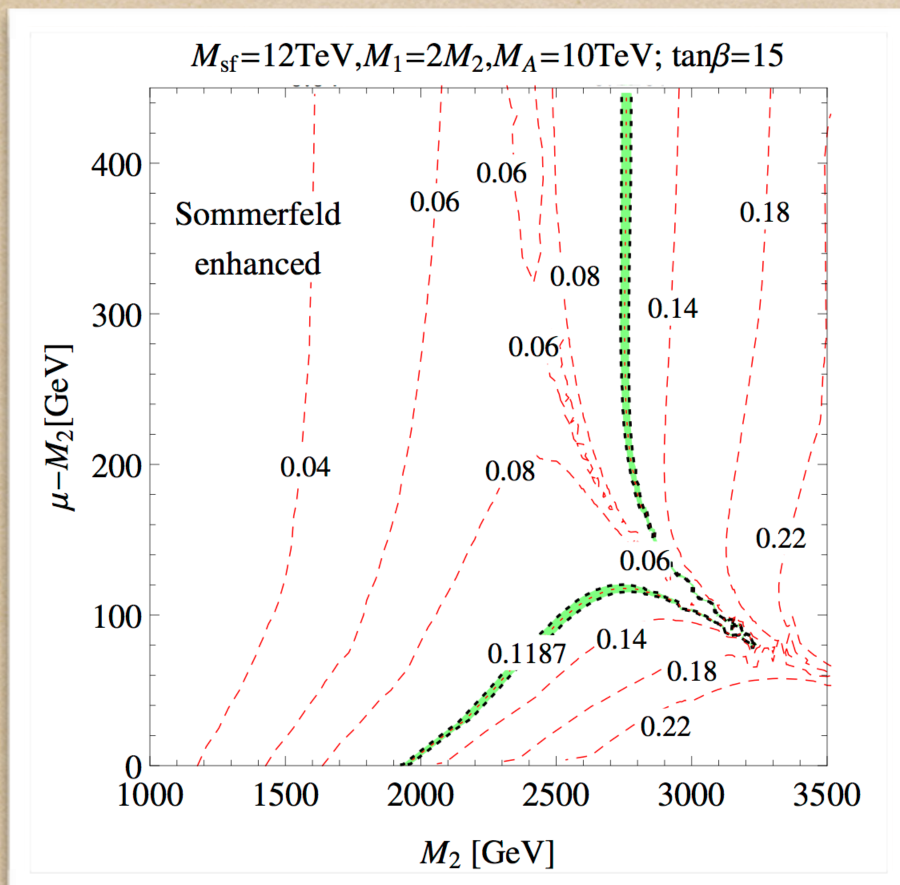

The correct relic density is moved from 1.7-2.2 TeV up to 1.9-3.3 TeV

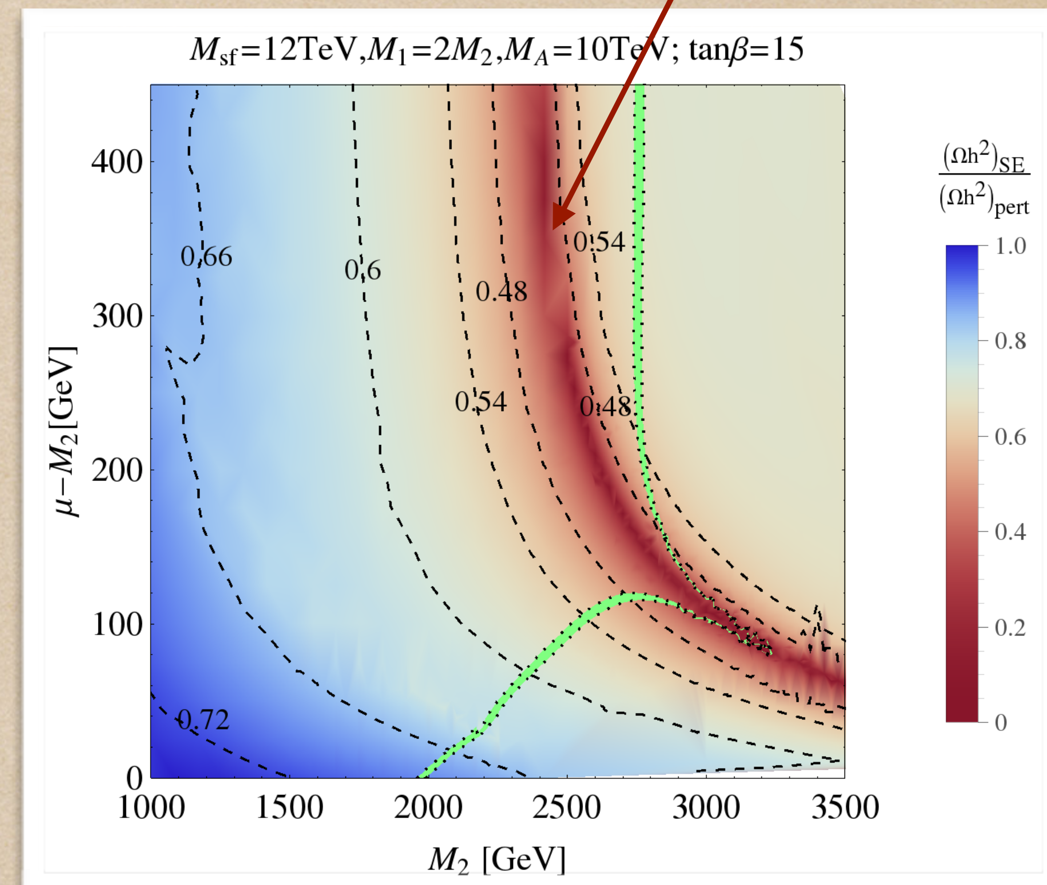
The position of the resonance is strongly $\mu$ dependent

# RESULTS
## WINO-HIGGSINO ADMIXTURE

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

force range — Bohr radius

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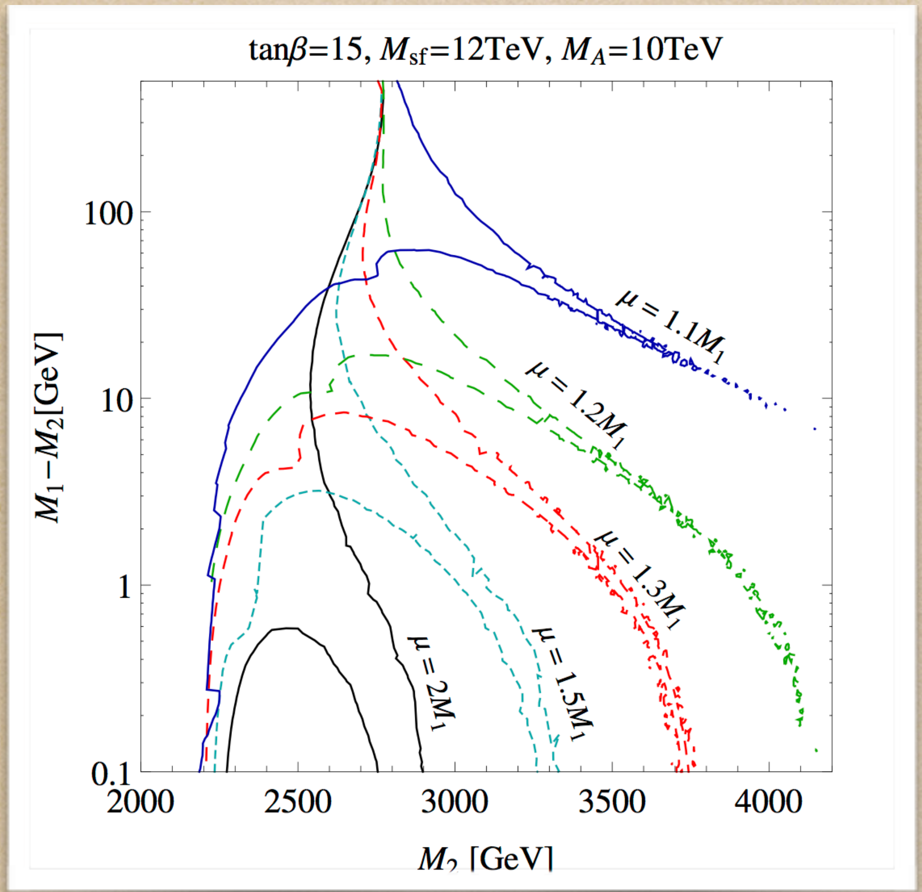
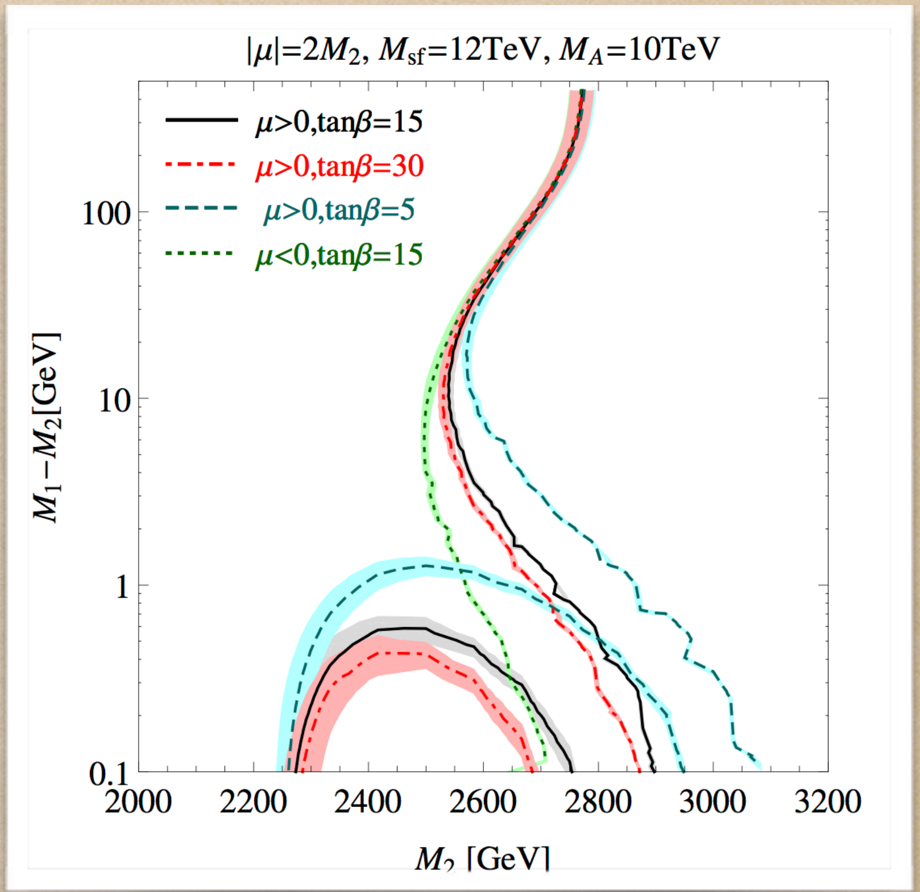
# RESULTS

## WINO-BINO ADMIXTURE - EFFECT OF *RESIDUAL PARAMETERS*



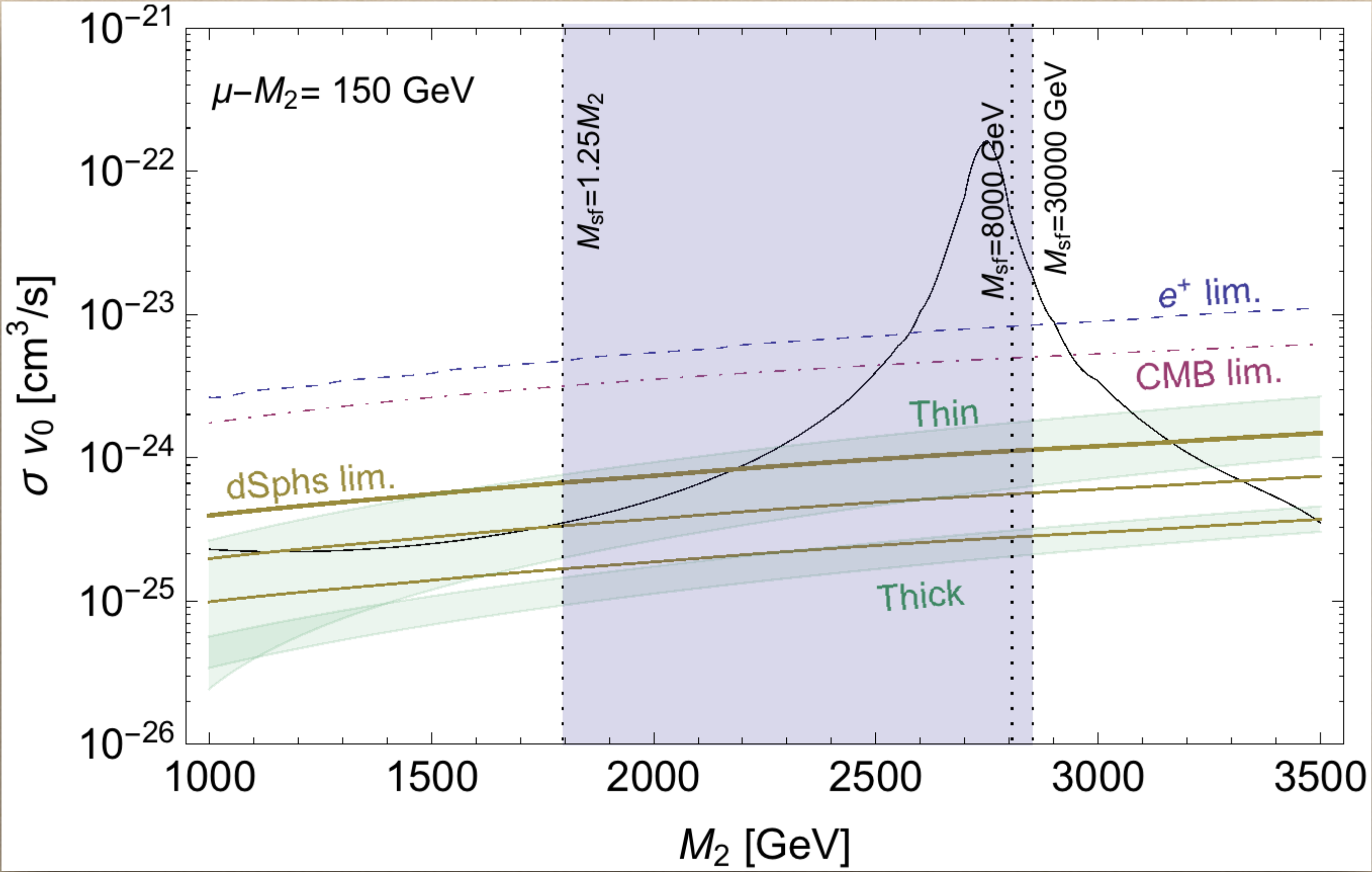

The position of the resonance is strongly dependent on choice of parameters controlling mixing, i.e. $\mu$ and $\tan\beta$

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

# Results

## Indirect Detection

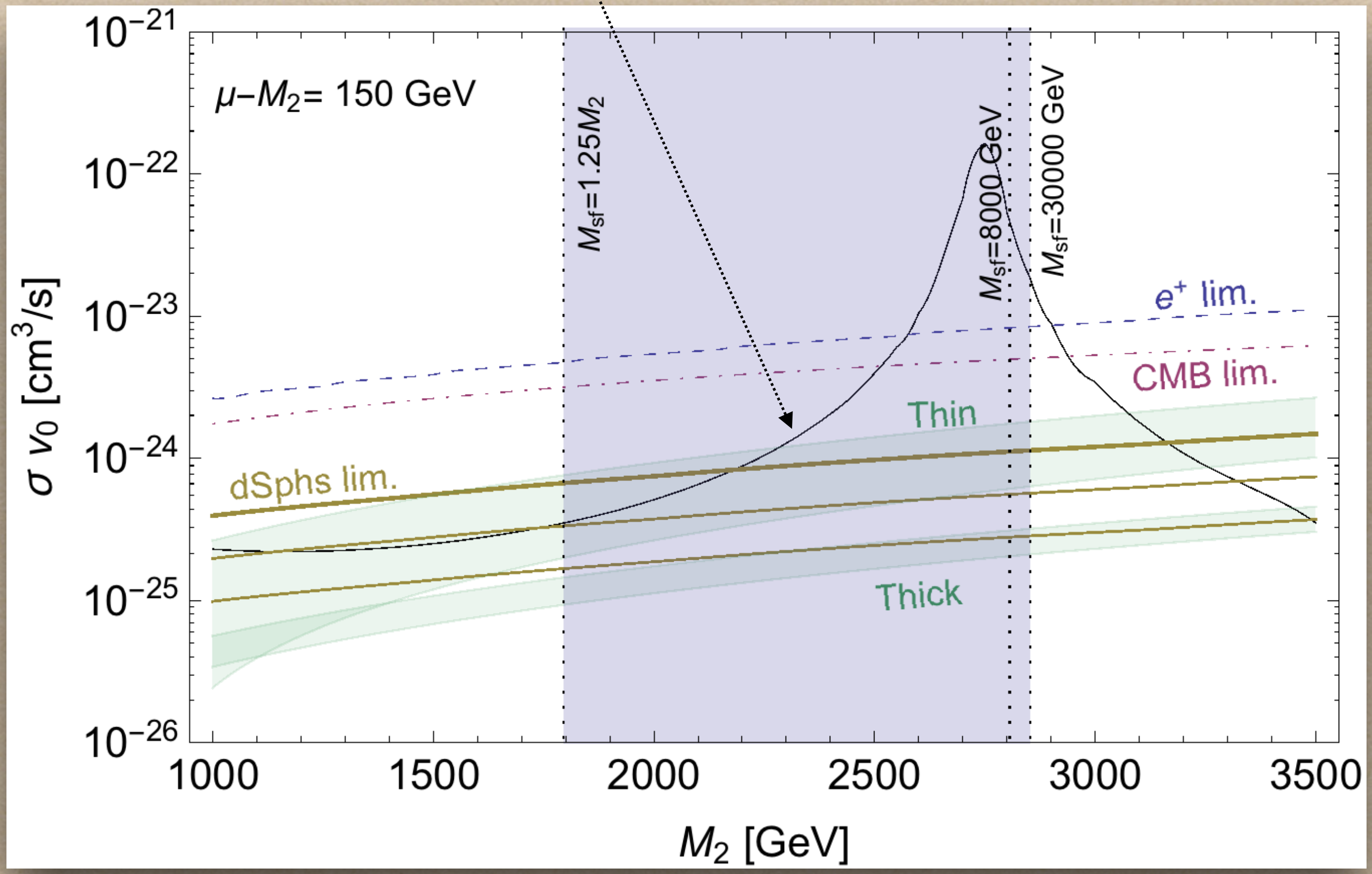
# Results
## EXAMPLE: WINO-HIGGSINO POINT




**similar study the pure Wino case: Ibe *et al.* '15**

# RESULTS
## EXAMPLE: WINO-HIGGSINO POINT

actual
cross section

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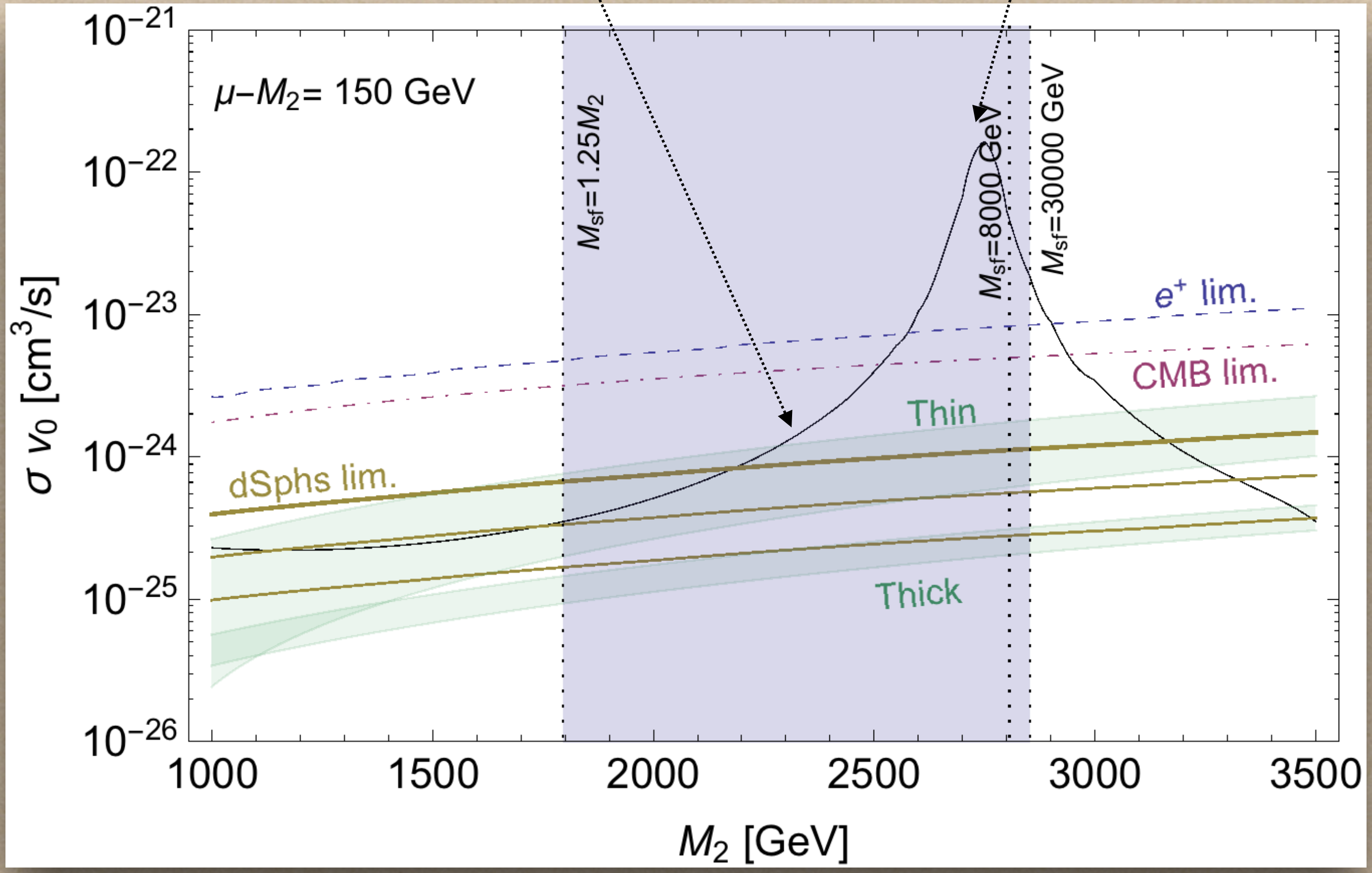
resonance moves
to the right
w.r.t. pure wino

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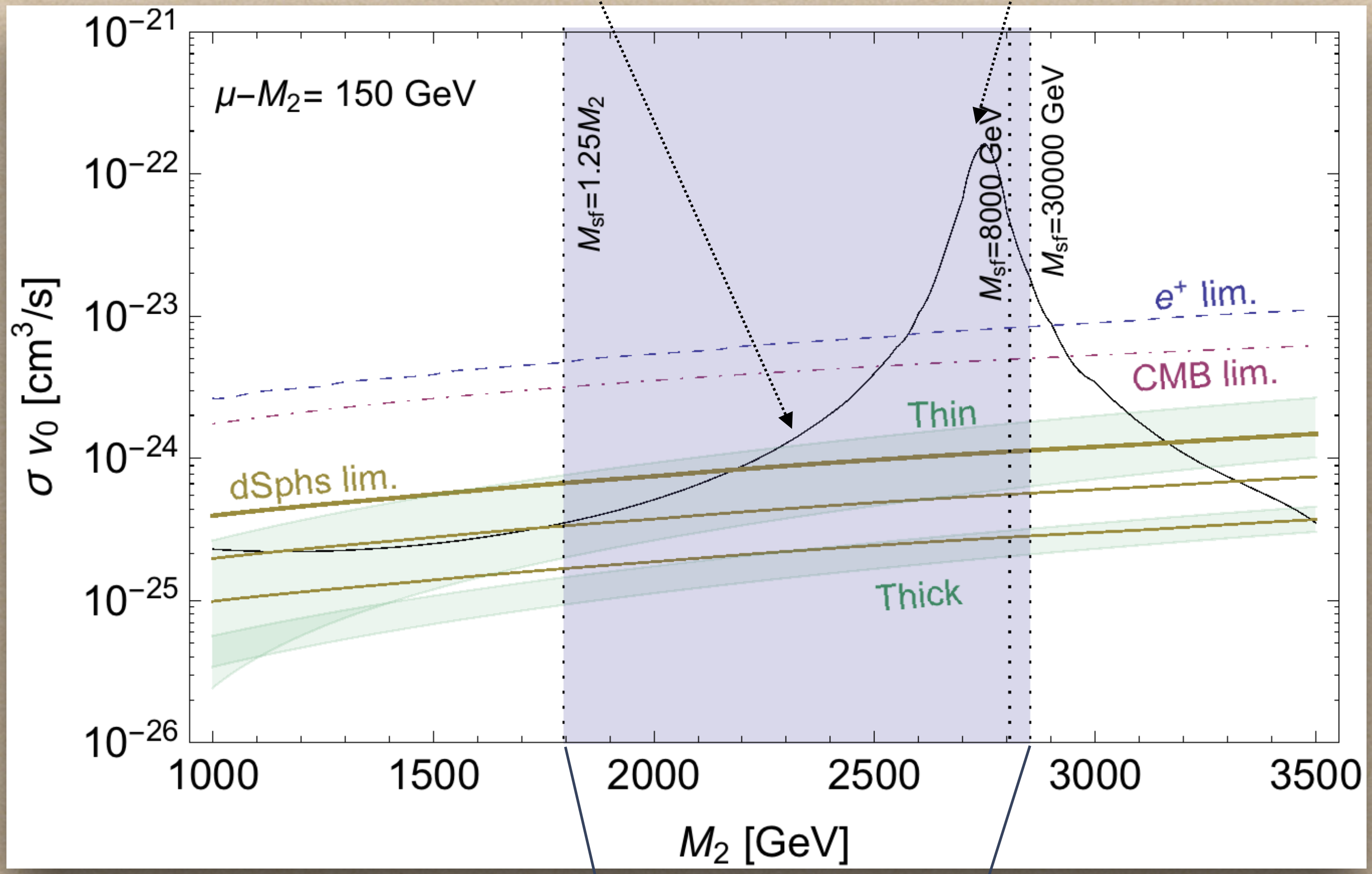


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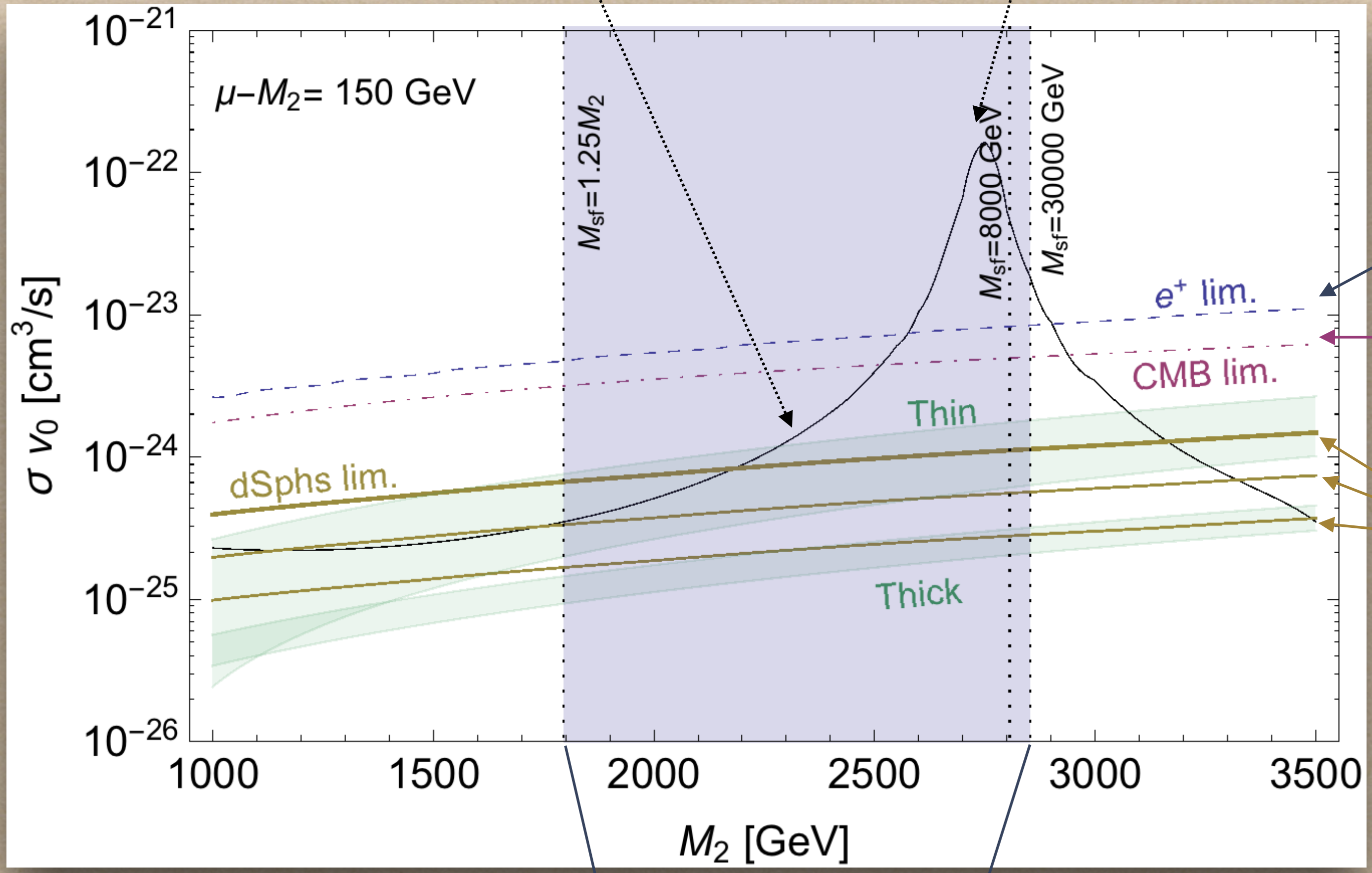


**Limits:**

AMS leptons

CMB limits
from Planck

Fermi +
MAGIC
dSphs

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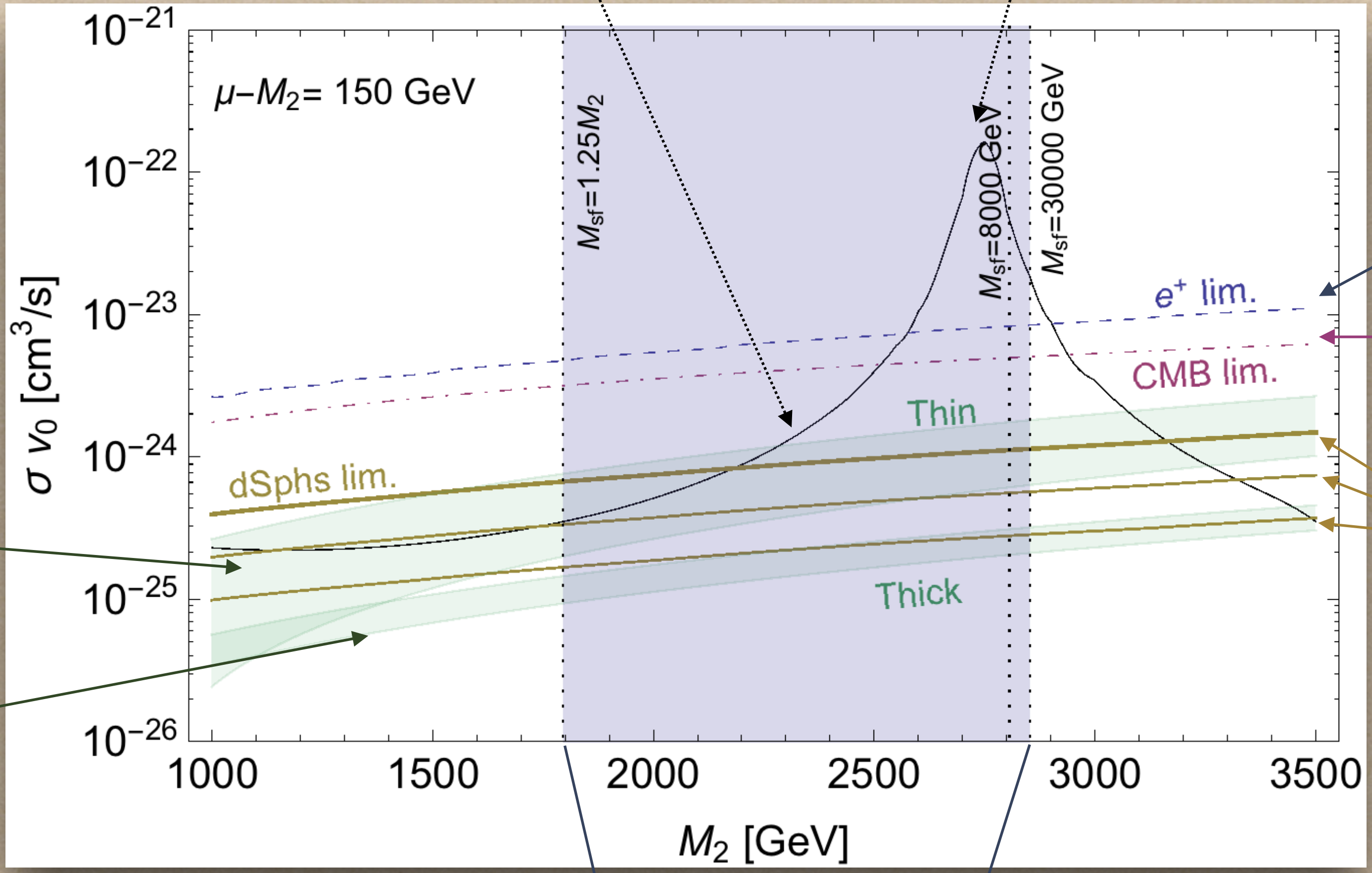
**Antiproton fits:**

Thin
prop. model

Thick
prop. model

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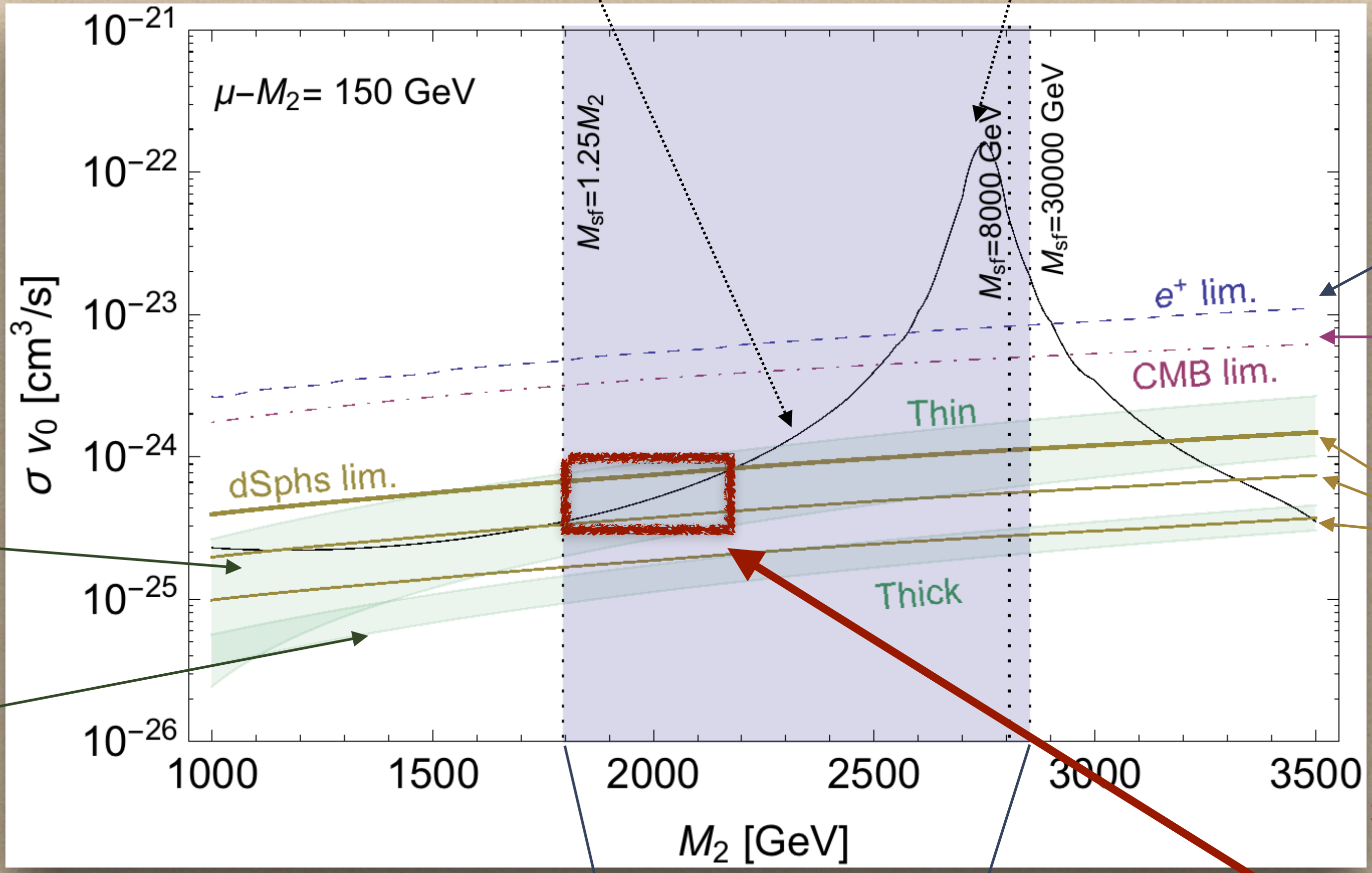


correct RD can be achieved:
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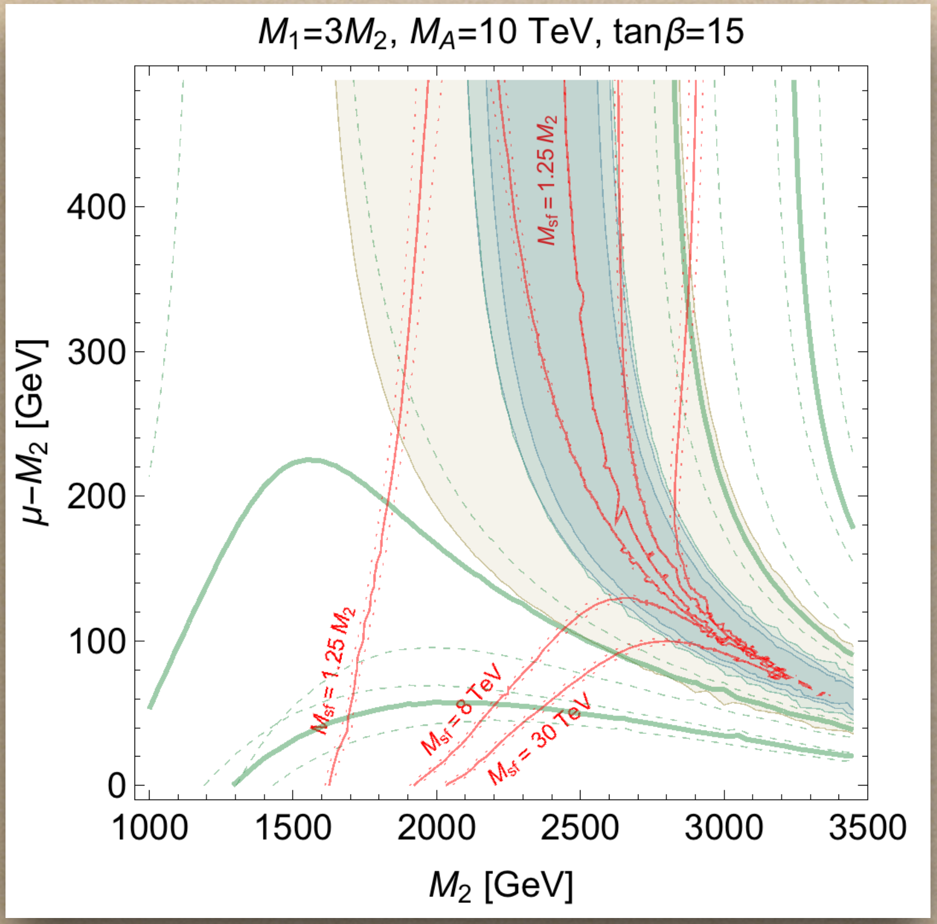
Region with:

1. correct thermal RD
2. allowed by ID data
3. preferred by AMS antiproton data

similar study the pure Wino case: Ibe *et al.* '15

# RESULTS
## WINO-HIGGSINO PLANE



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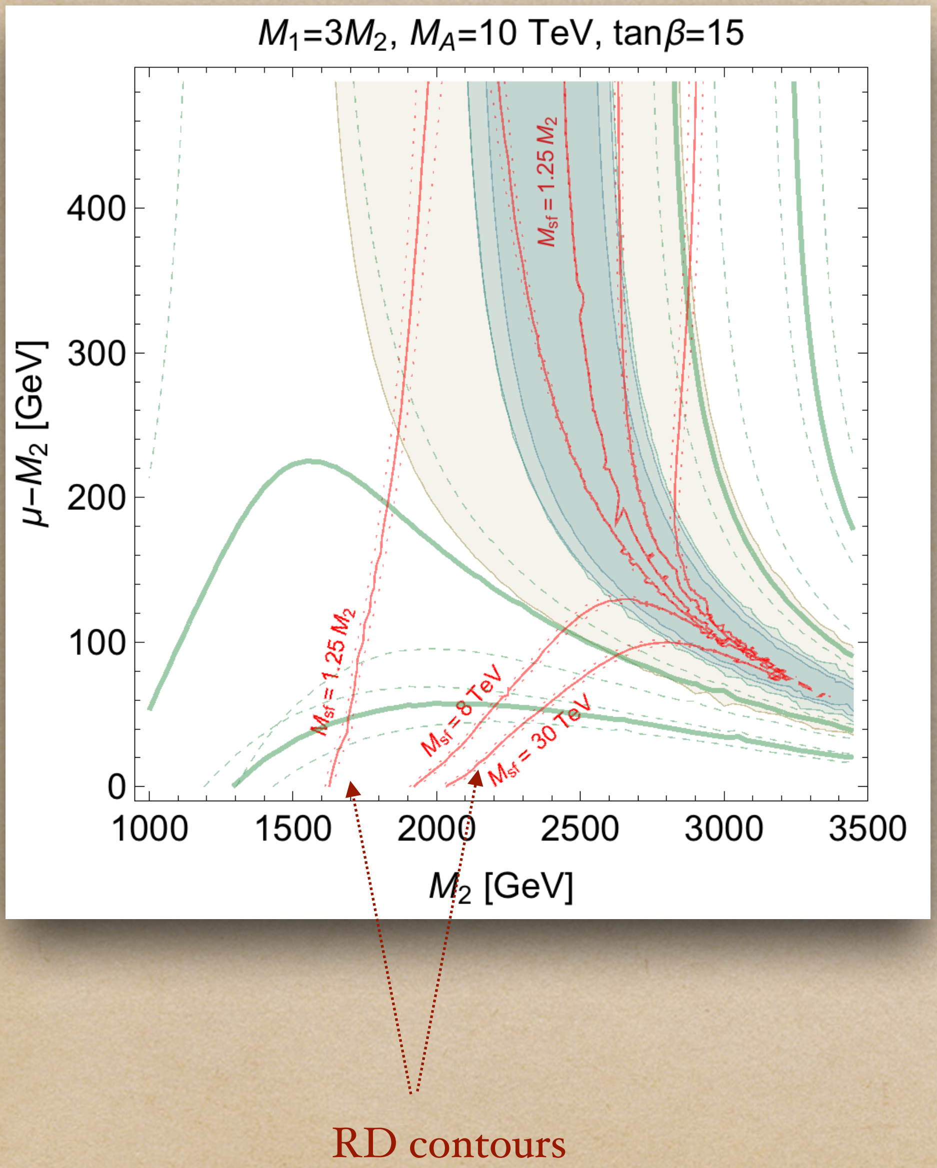
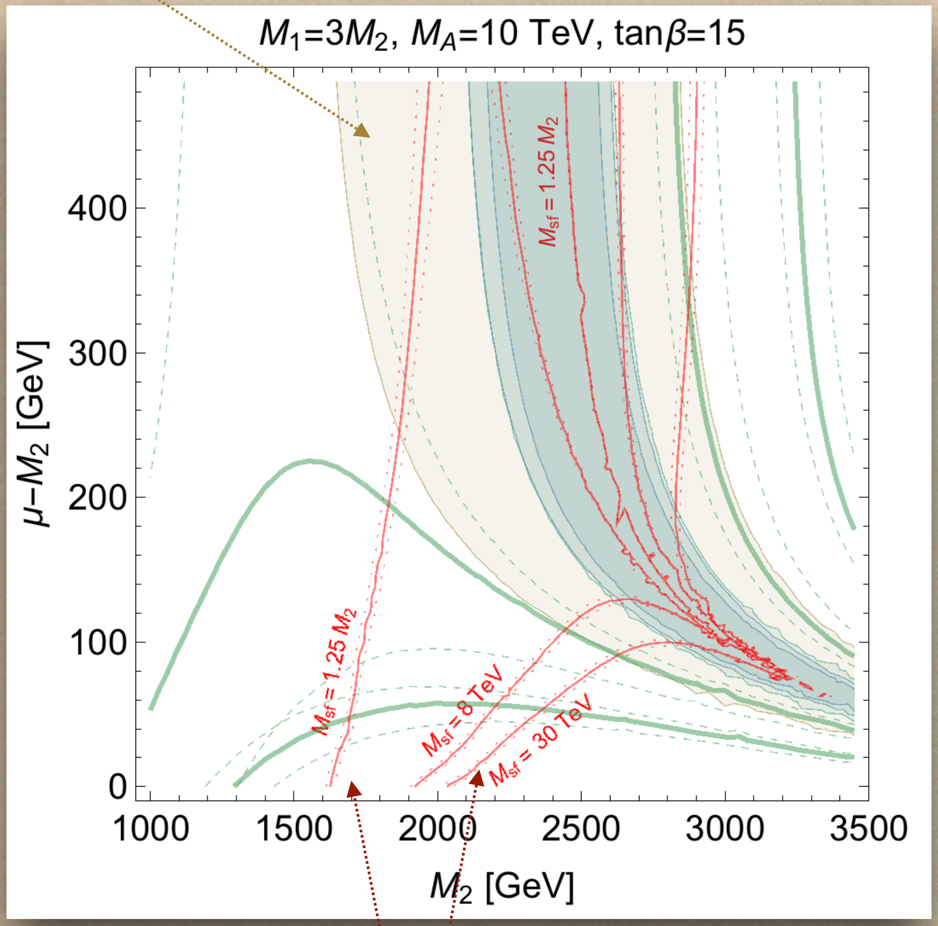


# RESULTS

## WINO-HIGGSINO PLANE

Fermi + MAGIC
dSphs
conservative lim.




RD contours

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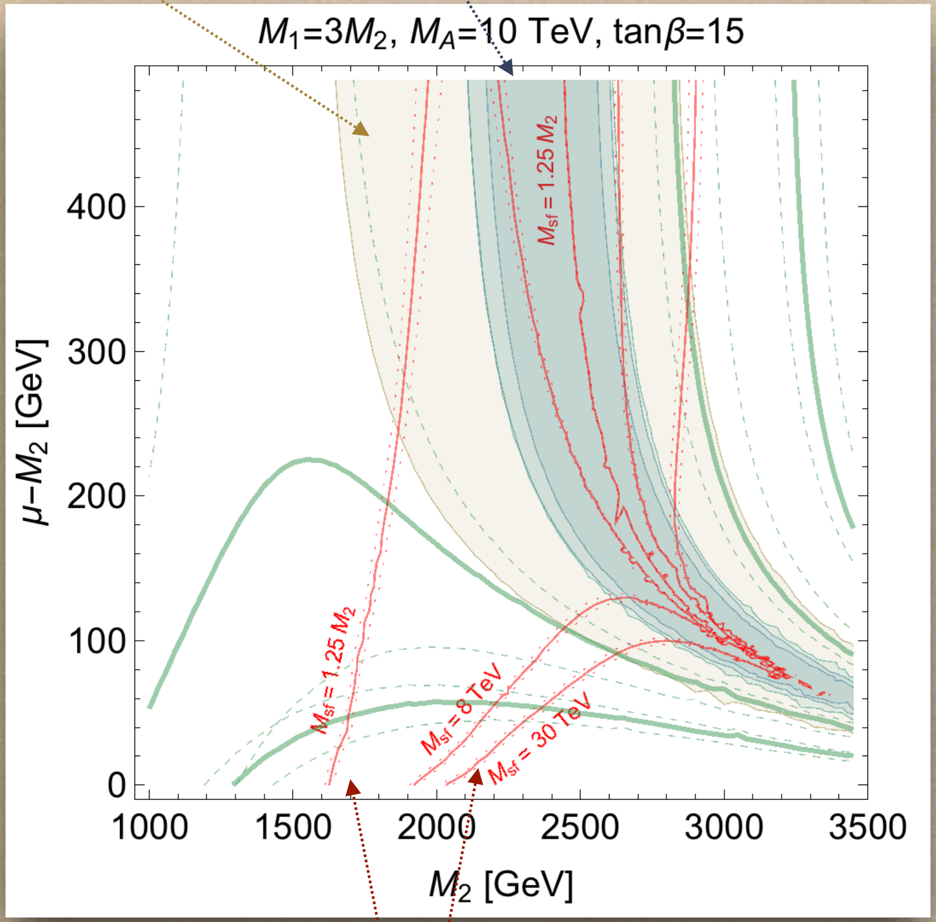
AMS leptons

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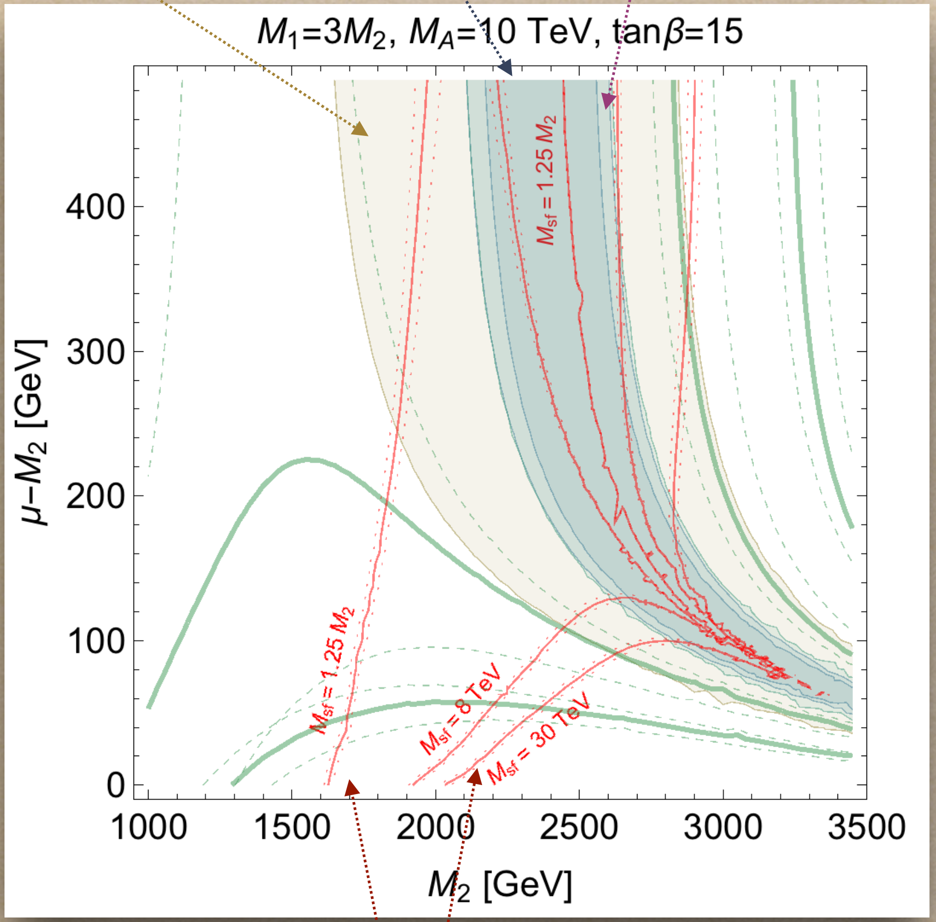
CMB limits from Planck

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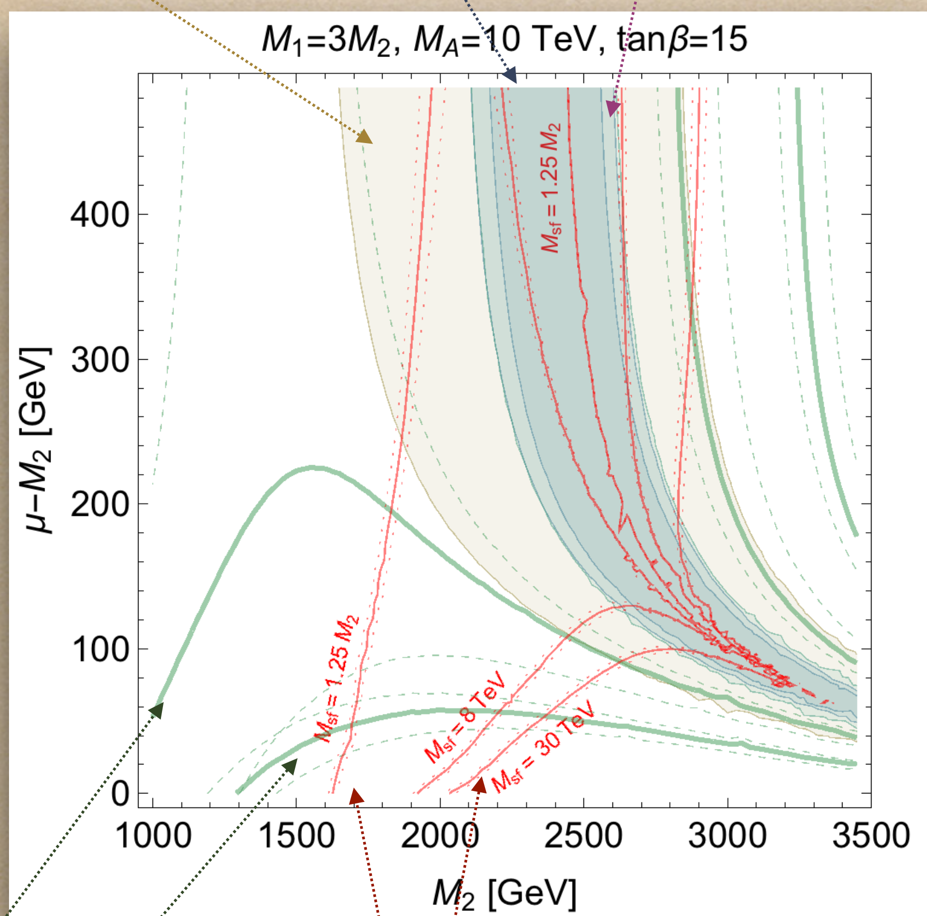


AMS Thin best fit

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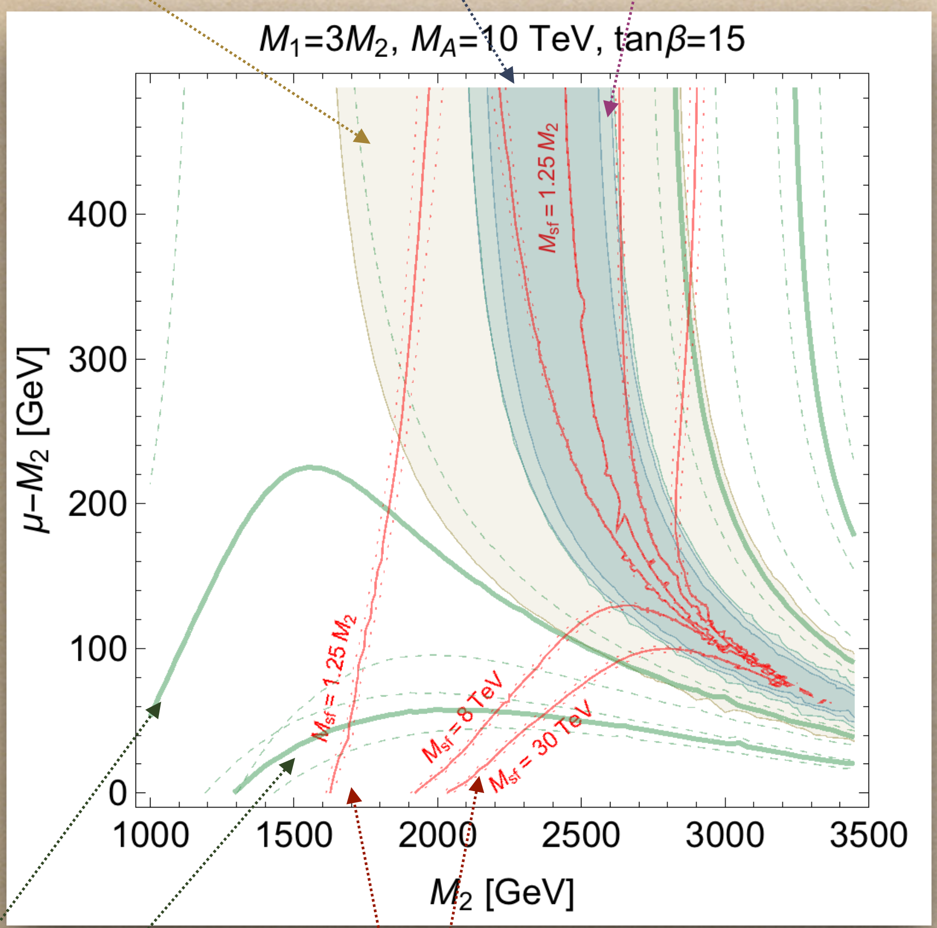


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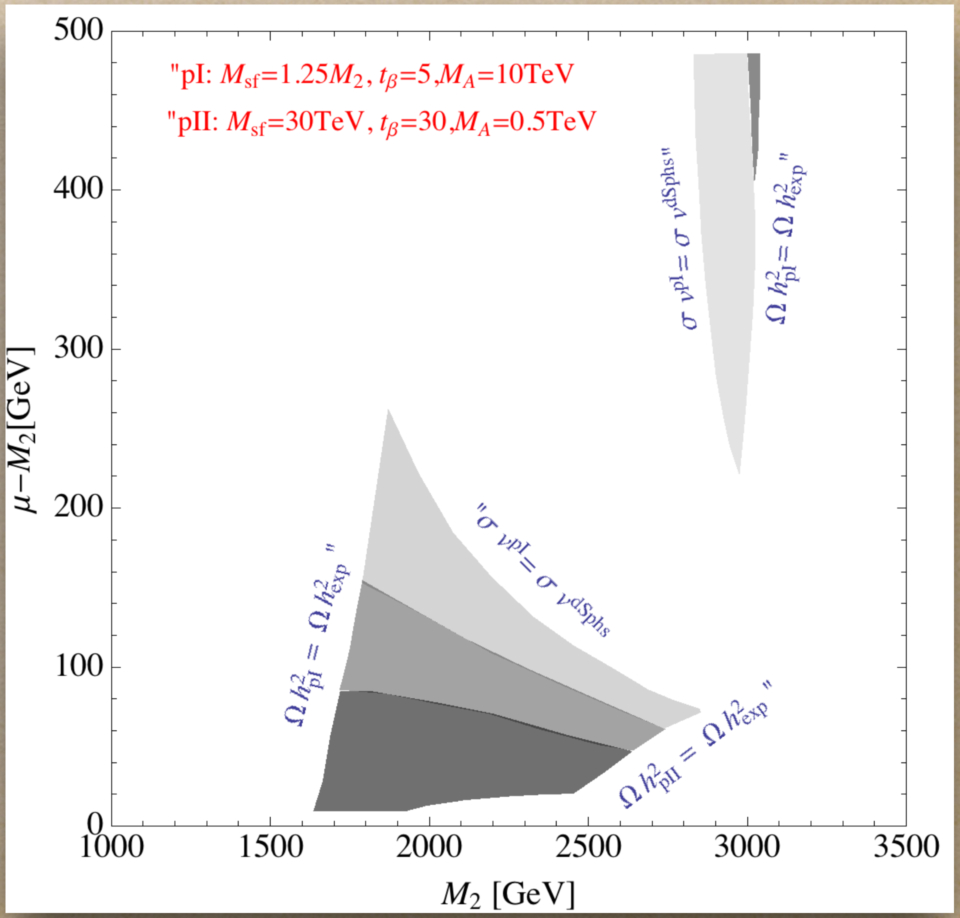
RD contours

Maximal possible region:

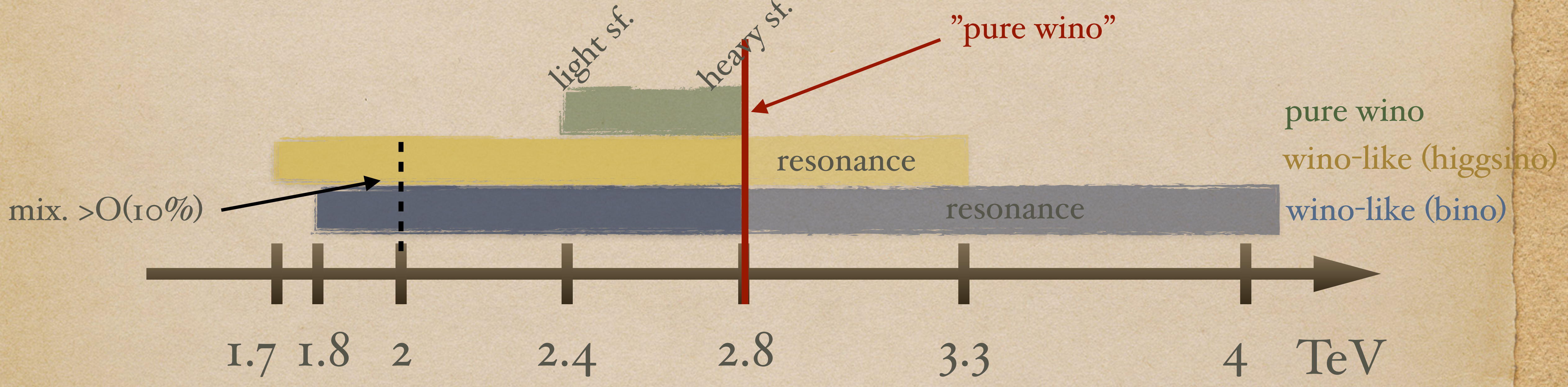
1. correct thermal RD
2. allowed by ID data
3. preferred by AMS antiproton data




gray scale: different dSphs limits

# CONCLUSIONS

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



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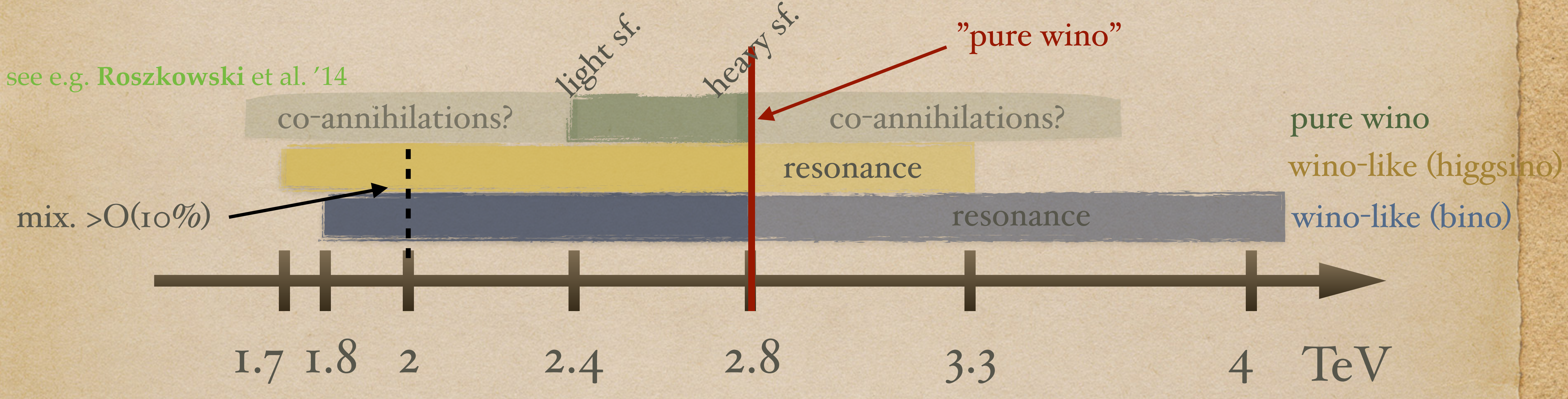

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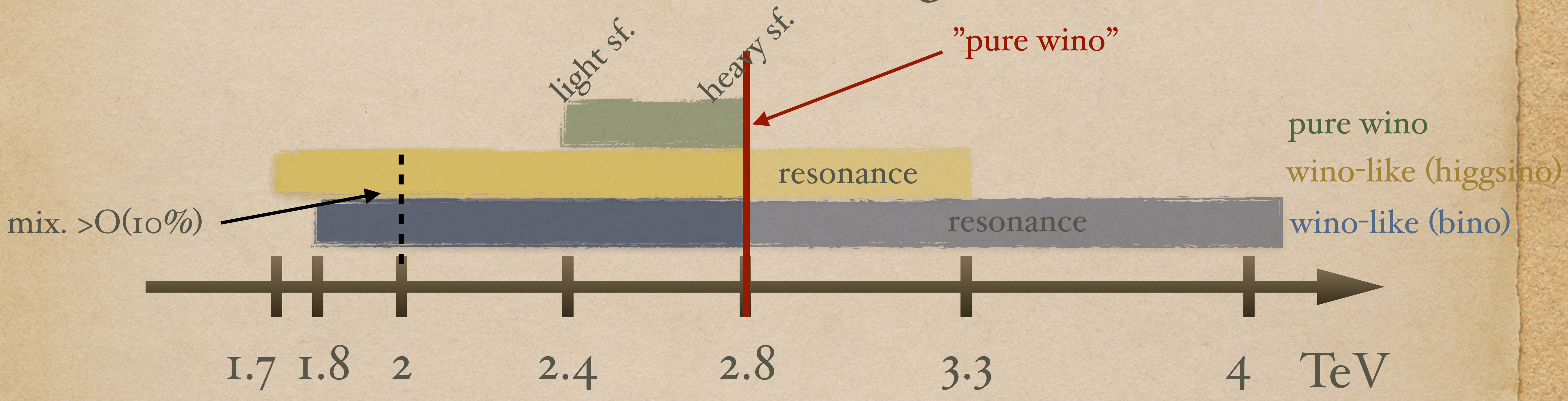


2. (Close to) resonance regions give detectable ID signals

(partially already constrained - partially promising for detection)

in particular: extended allowed region with correct RD and improving the AMS antiproton data fit exists

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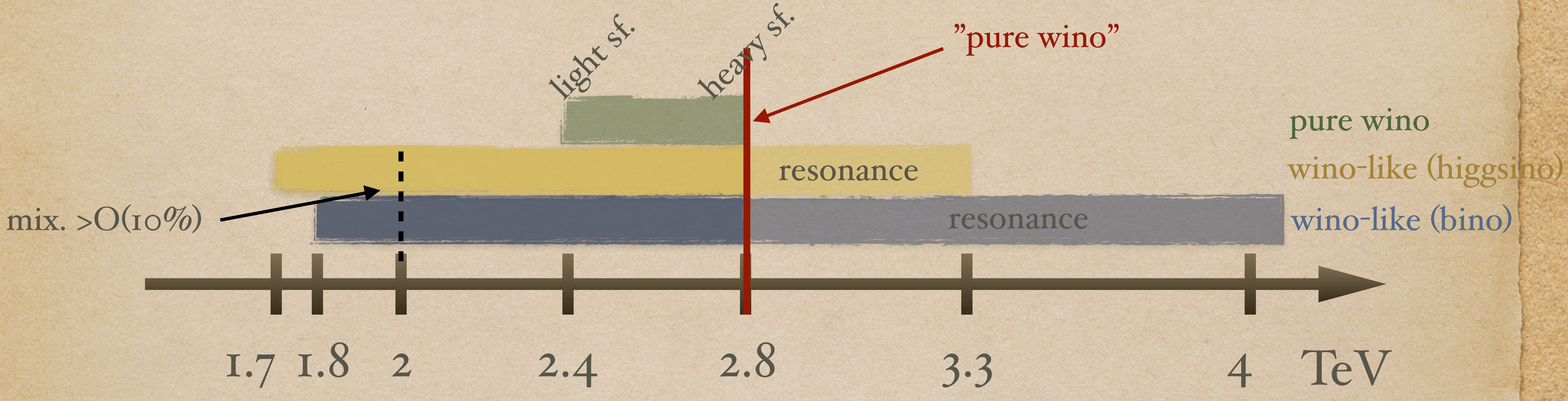


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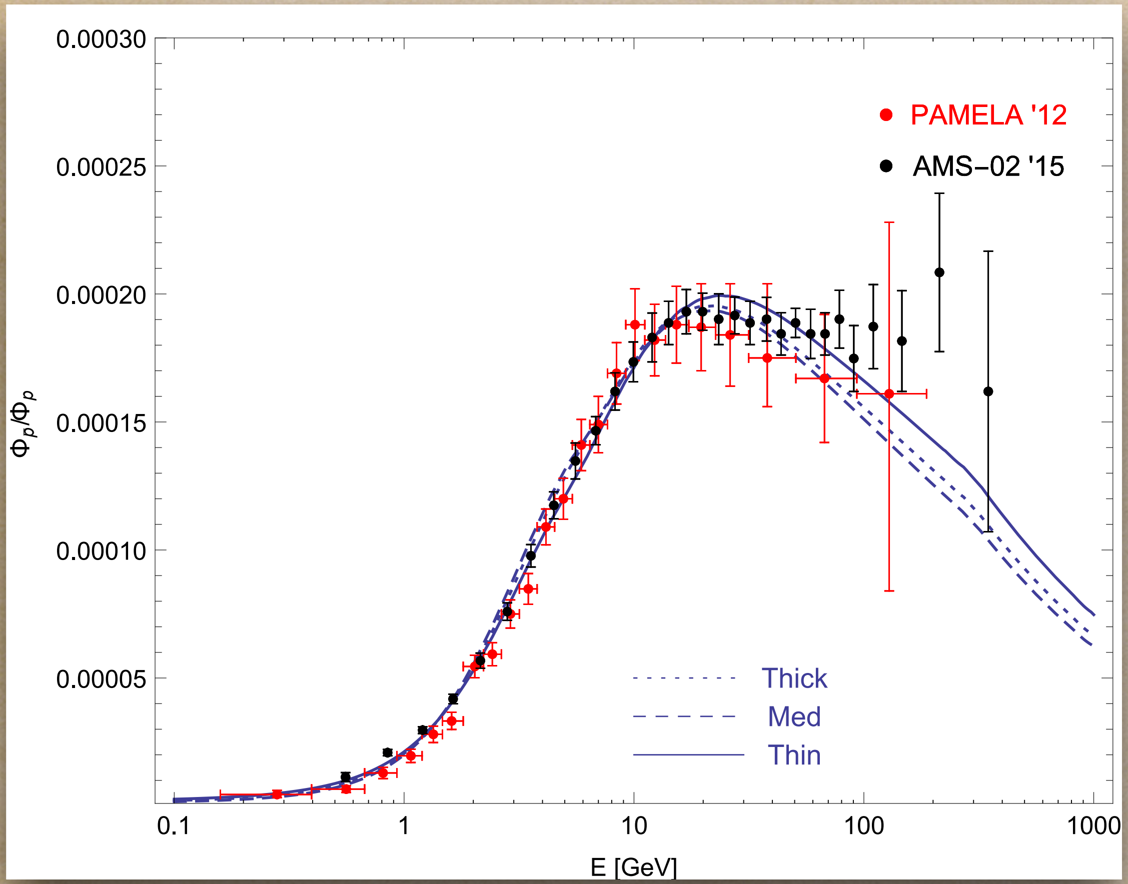
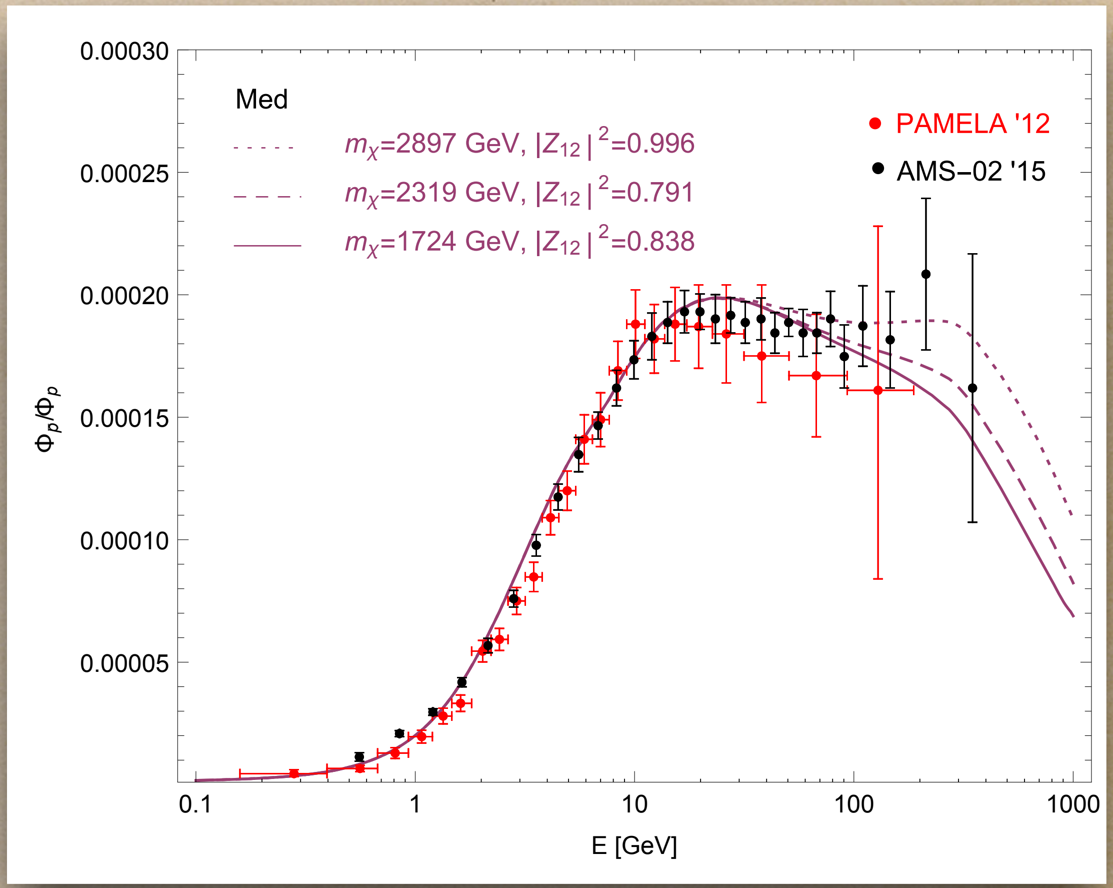
Public code including full SE in the MSSM with accuracy for relic density O(%) and running time O(min) to become available

# Backup Slides

# RESULTS
## ANTIPROTON / PROTON

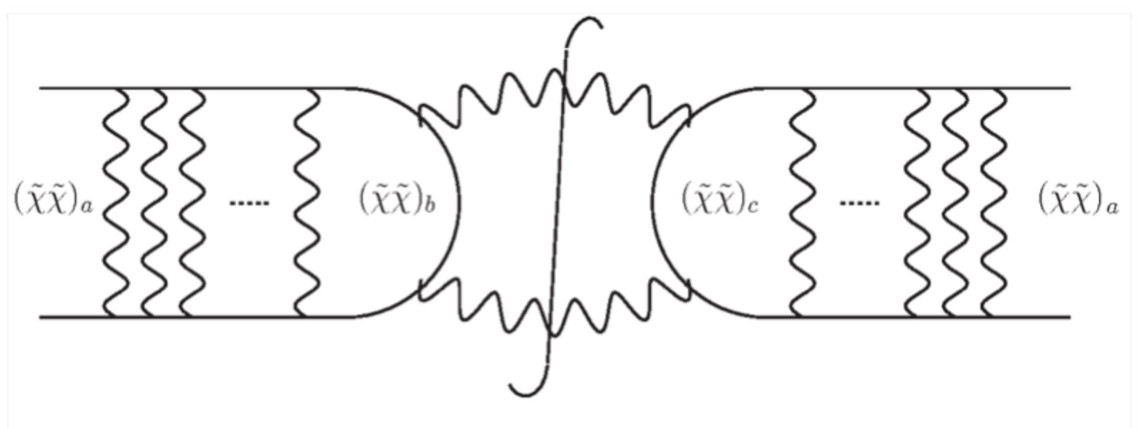



background only




background + DM

# Details of the Calculation




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

The full cross section:

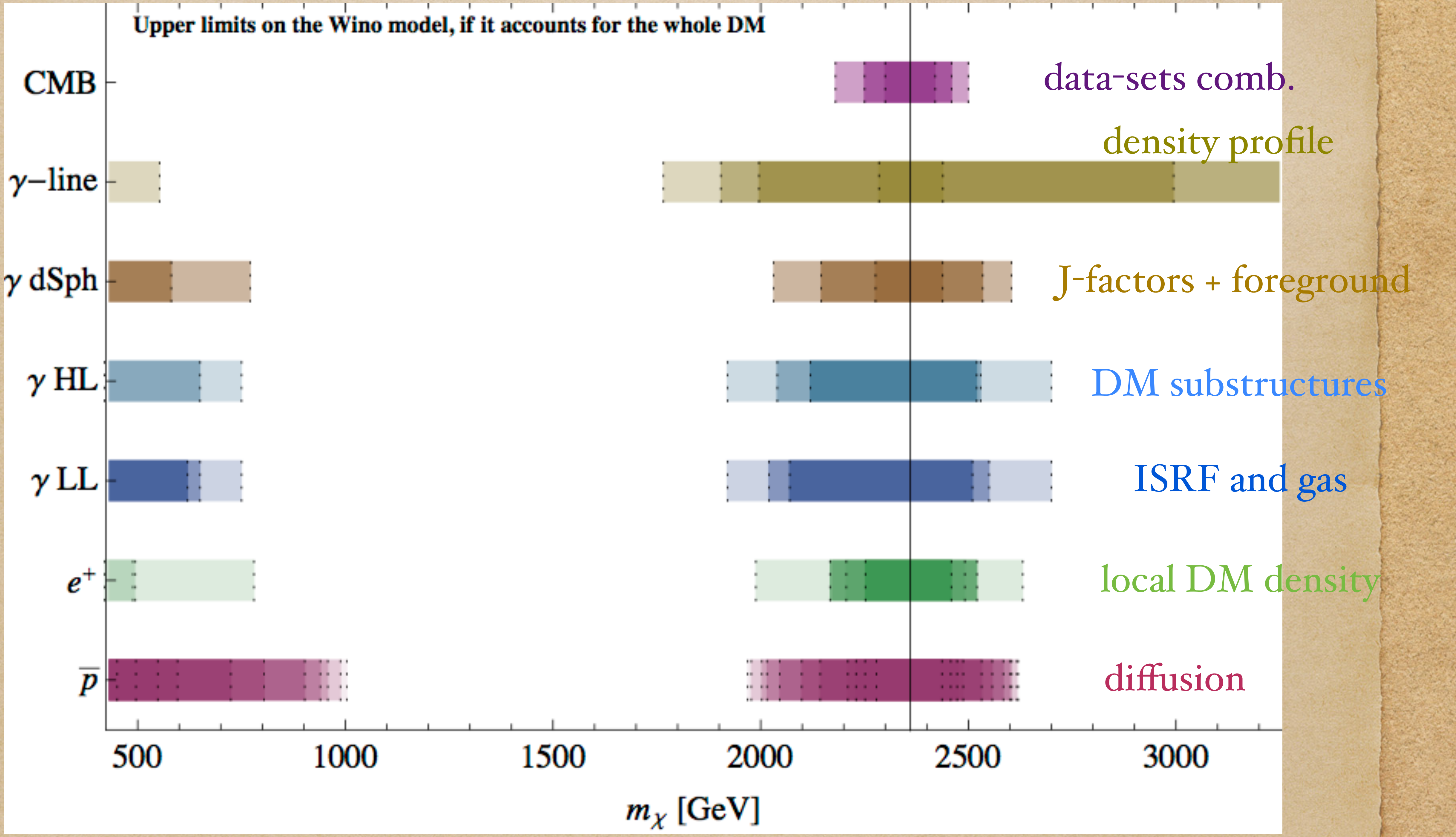
$$\sigma^{(\chi\chi)_a\to \text{ light}}\, v_{\text{rel}} = S_a[\hat{f}_h(^1S_0)]\ \hat{f}_{aa}(^1S_0) + S_a[\hat{f}_h(^3S_1)]\ 3\,\hat{f}_{aa}(^3S_1) + \frac{\vec{p}_a^{\,2}}{M_a^2}\Big( S_a[\hat{g}_\kappa(^1S_0)]\ \hat{g}_{aa}(^1S_0) + S_a[\hat{g}_\kappa(^3S_1)]\ 3\,\hat{g}_{aa}(^3S_1) + S_a\left[\frac{\hat{f}(^1P_1)}{M^2}\right]\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

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

Sommerfeld factors:

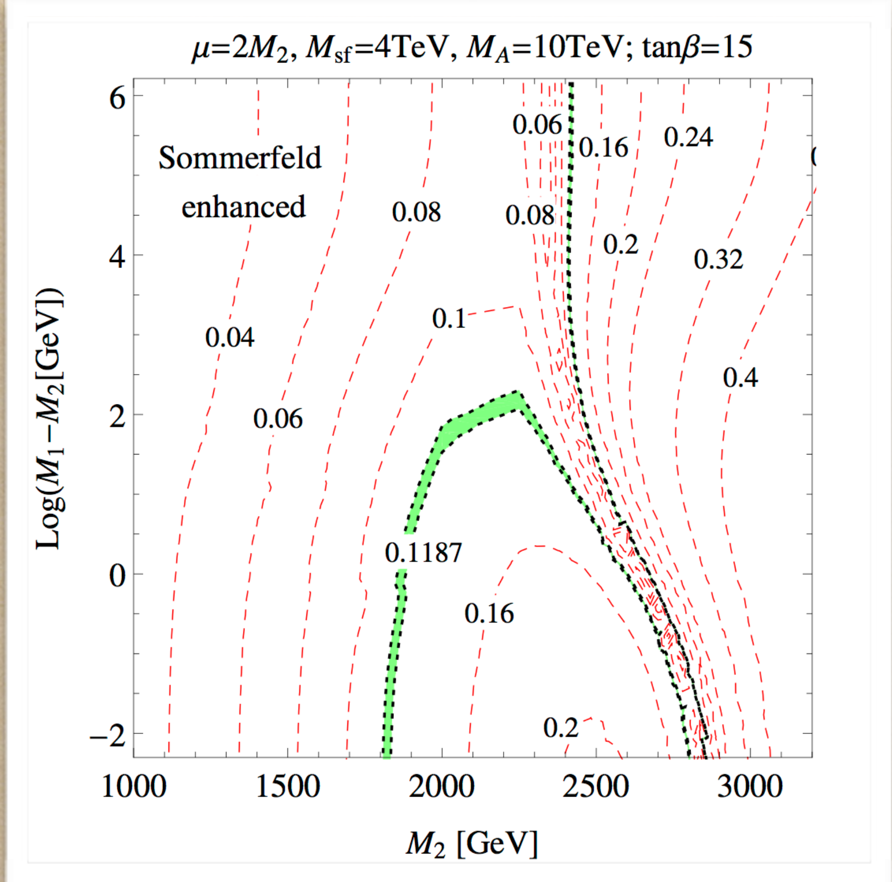
$$S_a[\hat{f}(^{2S+1}L_J)] = \frac{\left[\psi^{(L,S)}_{ca}\right]^*\ \hat{f}^{\chi\chi\to\chi\chi}_{bc}(^{2S+1}L_J)\,\psi^{(L,S)}_{ba}}{\hat{f}^{\chi\chi\to\chi\chi}_{aa}(^{2S+1}L_J)}$$

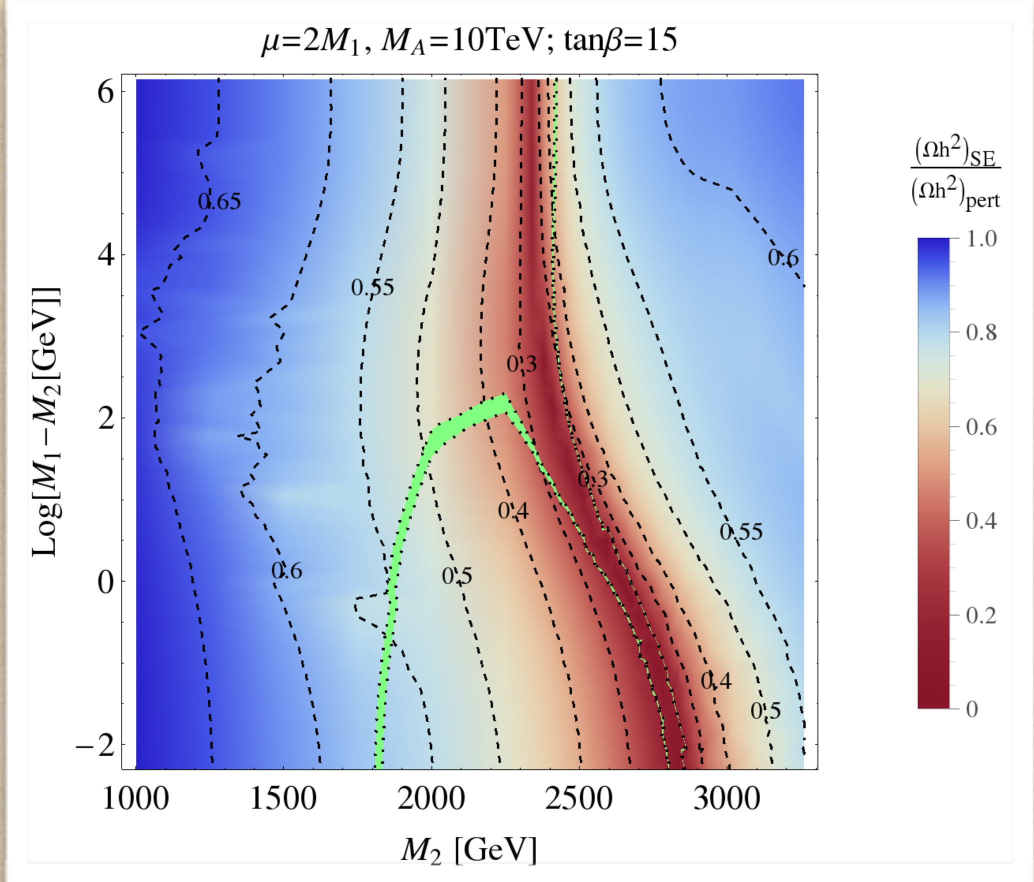
# LIMITS ON WINO DM
## UNCERTAINTIES




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

# 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