

# Relic density of wino-like dark matter in the MSSM

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*In collaboration with:*

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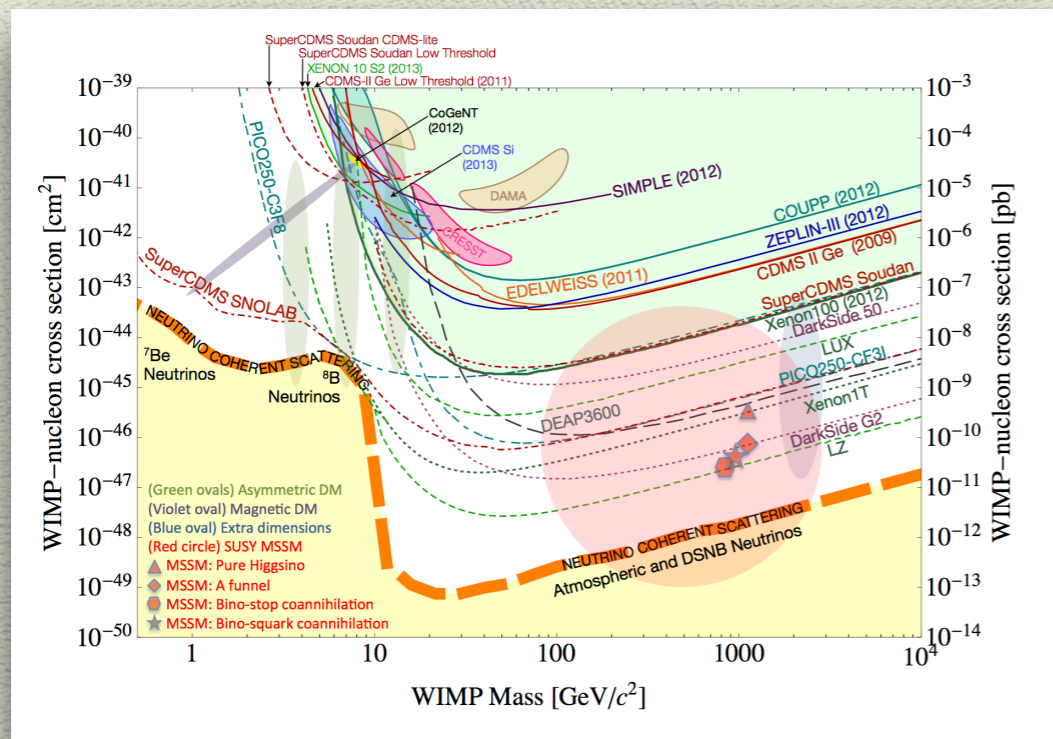
*S. Recksiegel and P. Ruiz-Femenia*

*to appear soon...*

# Motivations

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## Why heavy neutralinos as dark matter?



**ATLAS SUSY Searches\* - 95% CL Lower Limits**  
 Status: July 2015 ATLAS Preliminary  
 $\sqrt{s} = 7, 8 \text{ TeV}$

Model	$\epsilon, \mu, \tau, \gamma$	Jets	$E_{\text{miss}}$	$\int L d\tau [nb^{-1}]$	Mass limit	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$	Reference
<b>Inclusive Searches</b>	MSUGRA/CMSSM	0-3 $\epsilon, \mu, 1-2 \tau$	2-10 jets	3 b	Yes	20.3	20.3	1507.05525
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	mono-jet	1-3 jets	2-6 jets	Yes	20.3	20.3	1465.7875
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$ (Compressed)	2 $\epsilon, \mu$ (off-Z)	2 jets	Yes	20.3	20.3	20.3	1507.05525
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	0	2-6 jets	Yes	20.3	20.3	20.3	1465.7875
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	0-1 $\epsilon, \mu$	2-6 jets	Yes	20	20	20	1507.05525
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	2 $\epsilon, \mu$	0-3 jets	Yes	20.3	20.3	20.3	1501.03555
	GGM (bino NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	20.3	20.3	1407.0600
	GGM (higgsino NLSP)	7	1 b	Yes	20.3	20.3	20.3	1507.05493
	GGM (higgsino-bino NLSP)	2 $\epsilon, \mu$ (Z)	2 jets	Yes	20.3	20.3	20.3	1507.05493
	Graulin NLSP	0	mono-jet	Yes	20.3	20.3	20.3	1502.01518
<b><math>\tilde{\nu}</math> gen. squarks &amp; med.</b>	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	0	3 b	Yes	20.1	20.1	20.1	1407.0600
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	0	7-10 jets	Yes	20.3	20.3	20.3	1308.1841
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	0-1 $\epsilon, \mu$	3 b	Yes	20.1	20.1	20.1	1407.0600
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	0-1 $\epsilon, \mu$	3 b	Yes	20.1	20.1	20.1	1407.0600
<b><math>\tilde{\nu}</math> gen. squarks &amp; med. production</b>	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	0	2 b	Yes	20.1	20.1	20.1	1308.2631
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	2 $\epsilon, \mu$ (SS)	0-3 b	Yes	20.3	20.3	20.3	1404.2500
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	1-2 $\epsilon, \mu$	1-2 b	Yes	4.7, 20.3	4.7, 20.3	4.7, 20.3	1209.2102, 1407.0583
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	0	mono-jet+tag	Yes	20.3	20.3	20.3	1506.08616
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$ (natural GMSB)	2 $\epsilon, \mu$ (Z)	1 b	Yes	20.3	20.3	20.3	1407.0608
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	3 $\epsilon, \mu$ (Z)	1 b	Yes	20.3	20.3	20.3	1403.5222
<b>EW direct</b>	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	2 $\epsilon, \mu$	0	Yes	20.3	20.3	20.3	1403.5294
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	2 $\epsilon, \mu$	0	Yes	20.3	20.3	20.3	1403.5294
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	2 $\tau$	0	Yes	20.3	20.3	20.3	1407.0590
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	3 $\epsilon, \mu$	0	Yes	20.3	20.3	20.3	1402.7029
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	2-3 $\epsilon, \mu$	0-2 jets	Yes	20.3	20.3	20.3	1403.5284, 1402.7029
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	$\epsilon, \mu, \tau$	0-2 b	Yes	20.3	20.3	20.3	1501.07110
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	4 $\epsilon, \mu$	0	Yes	20.3	20.3	20.3	1405.5086
	GGM (bino NLSP) weak prod.	1 $\epsilon, \mu + \gamma$	-	Yes	20.3	20.3	20.3	1507.05493
<b>Long-lived particles</b>	Direct $\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$ prod., long-lived $\tilde{g}$	Disapp. trk	1 jet	Yes	20.3	20.3	20.3	1310.3675
	Direct $\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$ prod., long-lived $\tilde{q}$	dE/dx trk	-	Yes	18.4	18.4	18.4	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	27.9	27.9	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	Yes	19.1	19.1	19.1	1411.6795
	GMSB, stable $\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g} + \tau(\ell, \mu)$	1-2 $\mu$	-	Yes	537 GeV	537 GeV	537 GeV	1411.6795
	GMSB, $\tilde{q} \rightarrow \tilde{q} \tilde{g}$ , long-lived $\tilde{q}$	2 $\gamma$	-	Yes	20.3	20.3	20.3	1409.5542
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	displ. ee( $\mu$ )pp	-	Yes	20.3	20.3	20.3	1504.95162
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	displ. vtx + jets	-	Yes	20.3	20.3	20.3	1504.95162
<b>RPV</b>	LFV $pp \rightarrow \tilde{q}, \tilde{q} + X, \tilde{q} \rightarrow \tilde{q} \tilde{g} / \tau \mu$	$\epsilon, \mu, \tau$	-	Yes	20.3	20.3	20.3	1503.04430
	Bilinear RPV CMSSM	2 $\epsilon, \mu$ (SS)	0-3 b	Yes	20.3	20.3	20.3	1404.2500
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	4 $\epsilon, \mu$	-	Yes	20.3	20.3	20.3	1405.5086
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	3 $\epsilon, \mu + \tau$	-	Yes	20.3	20.3	20.3	1405.5086
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	0	6-7 jets	Yes	20.3	20.3	20.3	1502.05686
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	0	6-7 jets	Yes	20.3	20.3	20.3	1502.05686
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	2 $\epsilon, \mu$ (SS)	0-3 b	Yes	20.3	20.3	20.3	1404.250
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	2 $\epsilon, \mu$	2 jets + 2 b	Yes	20.3	20.3	20.3	ATLAS-COIN-2015-026
	$\tilde{g}, \tilde{q} \rightarrow \tilde{q} \tilde{g}$	2 $\epsilon, \mu$	2 b	Yes	20.3	20.3	20.3	ATLAS-COIN-2015-015
<b>Other</b>	Scalar charm, $\tilde{c} \rightarrow \tilde{c} \tilde{g}$	0	2 c	Yes	20.3	20.3	20.3	1501.01325

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 $\sigma$  theoretical signal cross section uncertainty.

Direct detection limits stronger for WIMP masses  $\mathcal{O}(100 \text{ GeV})$

No signs of new physics at the LHC

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

# Motivations

Why precision calculations are needed?

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

*Planck + lensing + BAO, '15*



uncertainty < 1%\*

\* does not change much  
when varying experimental  
data combinations

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Why precision calculations are needed?

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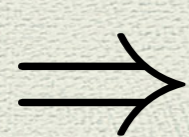
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Widely used codes e.g. DarkSUSY, micrOMEGAs have comparable **numerical precision**, but cross sections at tree level



**theoretical uncertainty**  
significantly larger!

loop corrections

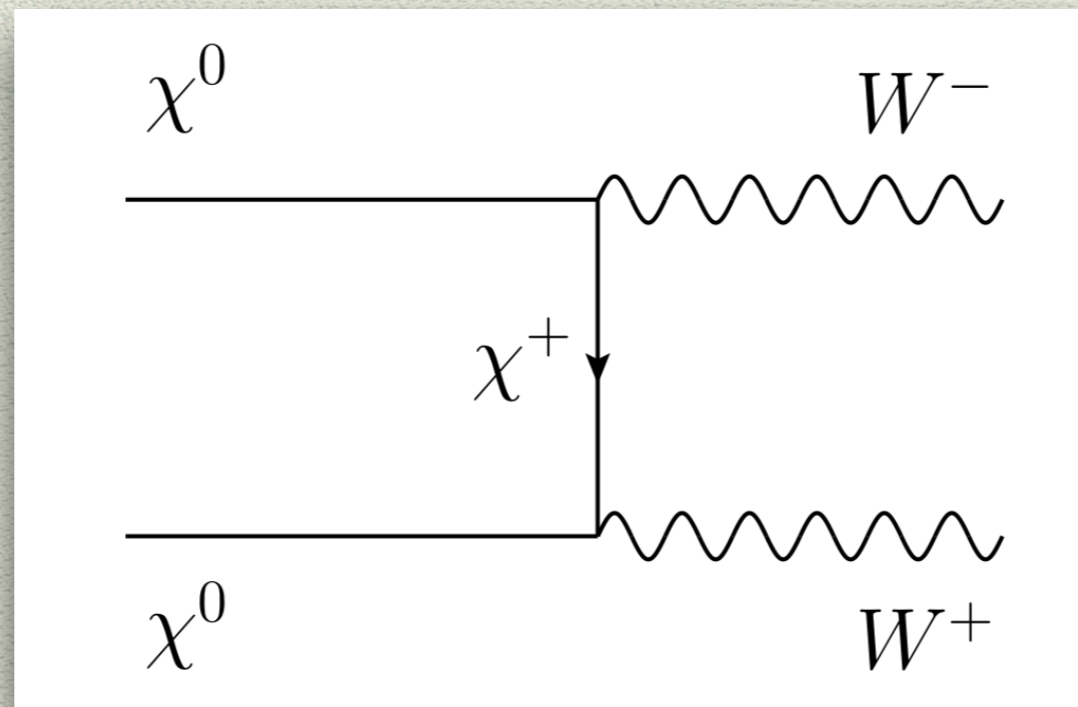
LL resummation  
Sommerfeld enhancement

**Goal: calculate relic density with Sommerfeld effect in the full MSSM**

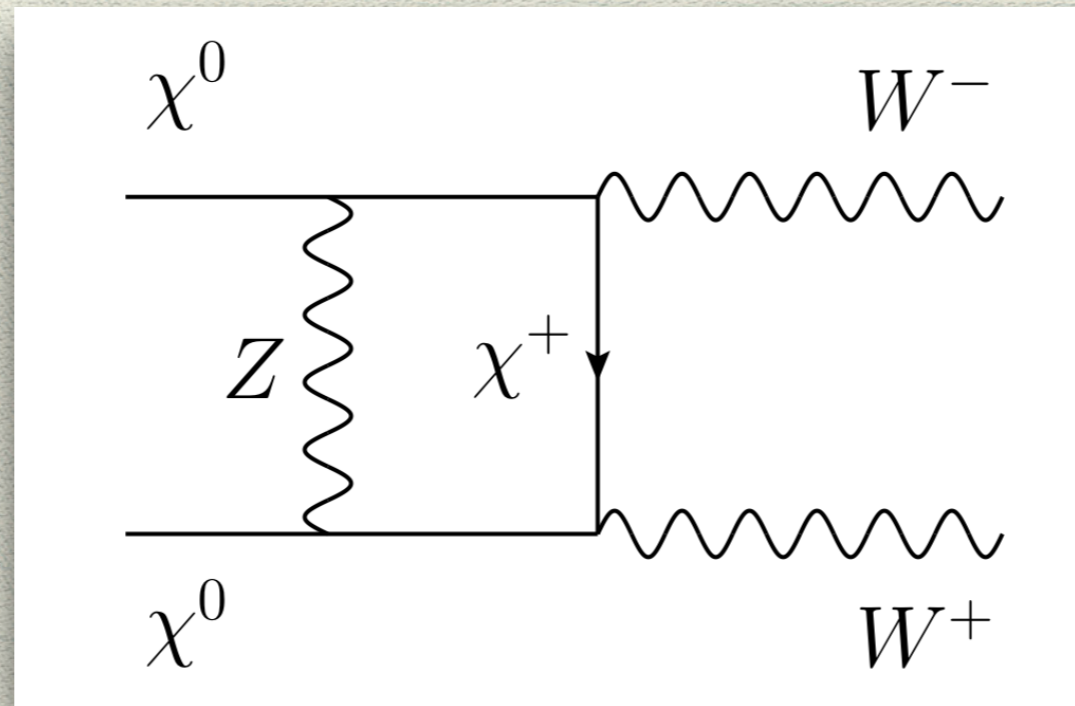
# The Sommerfeld enhancement

# The Sommerfeld enhancement from electroweak interaction

Tree level contribution to the cross section  $\mathcal{M}_0$



1-loop correction  $\mathcal{M}_1$



Non-relativistic regime:  $\alpha^2 m_\chi \gtrsim m_\chi v^2$   
Bohr energy kinetic energy

Low mediator mass:  $\frac{1}{m_Z} \gtrsim \frac{1}{\alpha m_\chi}$   
force range Bohr radius

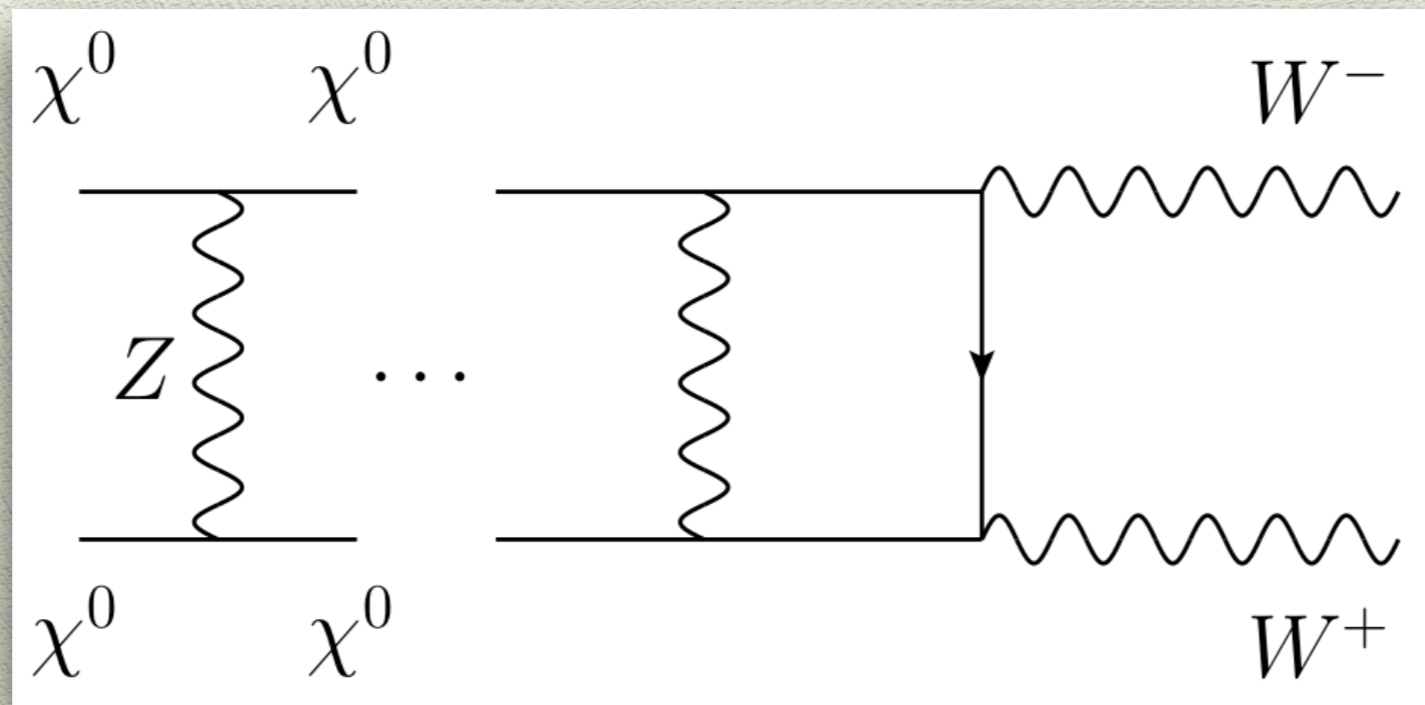
$$\Rightarrow \mathcal{M}_1 \sim \frac{\alpha m_\chi}{m_Z} \mathcal{M}_0$$

O(1), no suppression!



n-loop diagram:  $\mathcal{M}_n \sim \left( \frac{\alpha m_\chi}{m_Z} \right)^n \mathcal{M}_0$

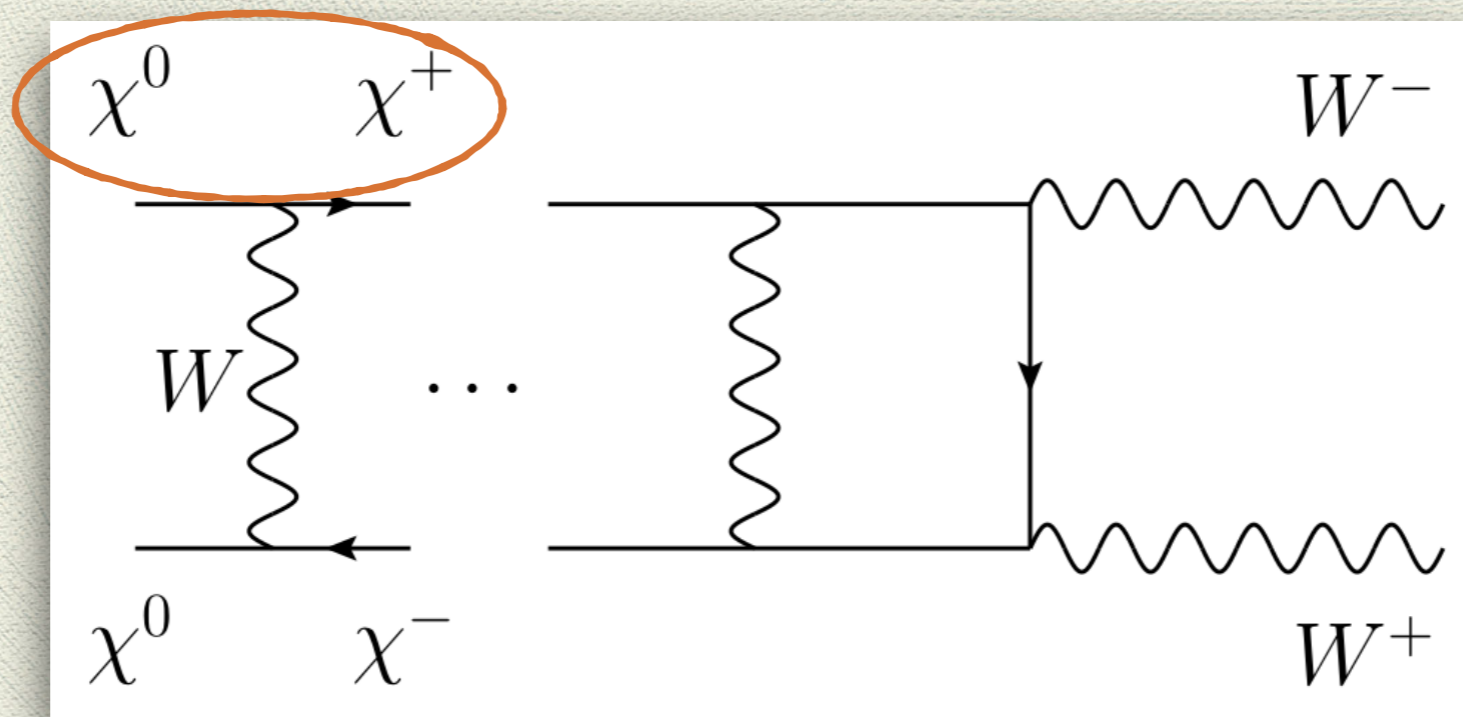
$\Rightarrow$  resummation of ladder diagrams is needed!



In the MSSM:  $Z, W, h^0, H^0, H^\pm$

n-loop diagram:  $\mathcal{M}_n \sim \left( \frac{\alpha m_\chi}{m_Z} \right)^n \mathcal{M}_0$

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In the MSSM:  $Z, W, h^0, H^0, H^\pm$

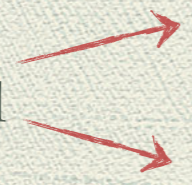
Small mass splitting:  $m_{\chi^\pm} - m_\chi \lesssim \alpha^2 m_\chi$   
Bohr energy

$\Rightarrow$  off-diagonal reactions

# New code (to be public):

Based on framework by Beneke, Hellmann, Ruiz-Femenia '12, '13, '14

## 1. Full MSSM

- previous results:
- pure wino, pure higgsino  
*Hisano et al. '04, '06*
  - mixed wino-higgsino (with everything else decoupled)  
*Hryczuk et al. '11, Beneke et al. '14*
  - stop and stau co-annihilations  
*Freitas '07, Hryczuk '11, Klasen et al. '14*
  - gluino co-annihilation  
*Ellis et al. '15*
  - Minimal DM model  
*Cirelli et al. '07, '08, '09*
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## 2. Sommerfeld effect for **P- and $O(v^2)$ S-wave**

## 3. **Off-diagonal** annihilation matrices

← not present in DarkSE  
*Hryczuk, '11*  
total effect up to  $O(10\%)$

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## 4. Present day annihilation in the halo (for ID)

total effect up to  $O(10\%)$

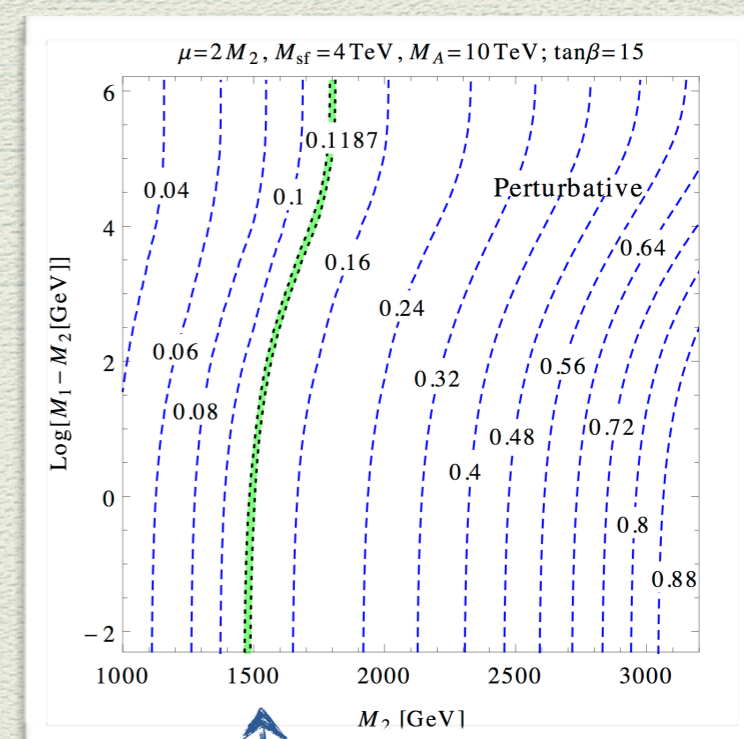
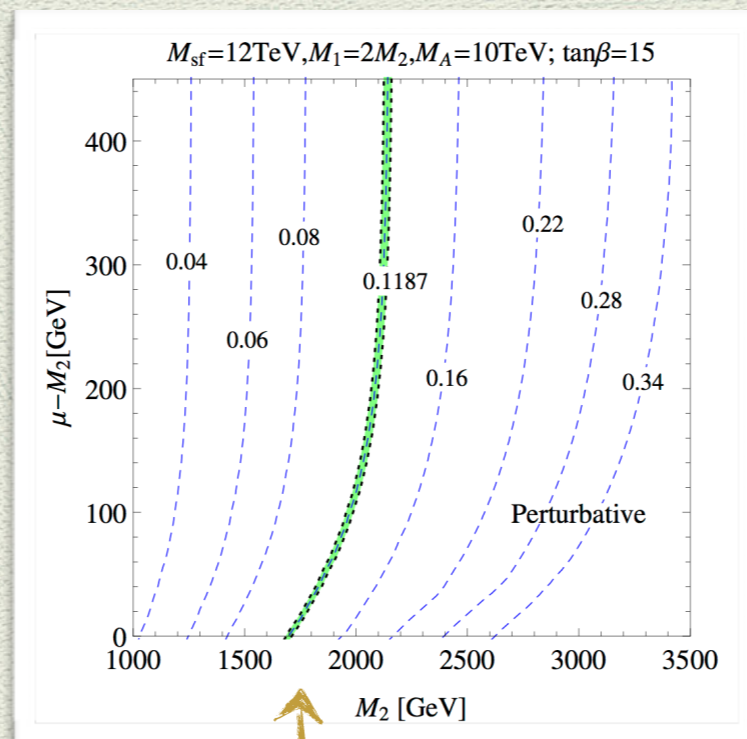
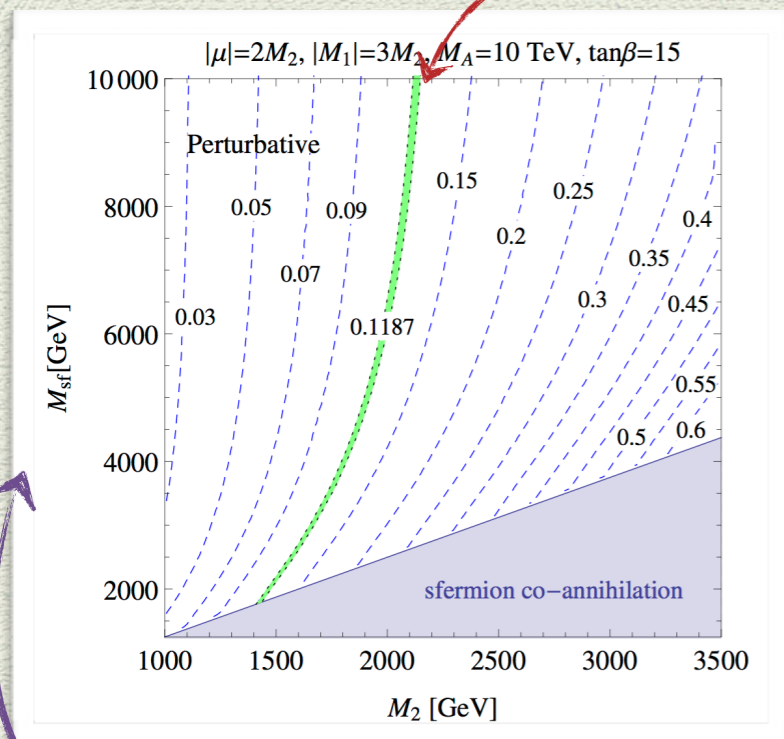
## 5. Accuracy at $O(\%)$ (NLO still missing...)

# Results

# Tree level results

Wino-like neutralino with higgsino or bino admixtures

"pure wino" 2.2 TeV



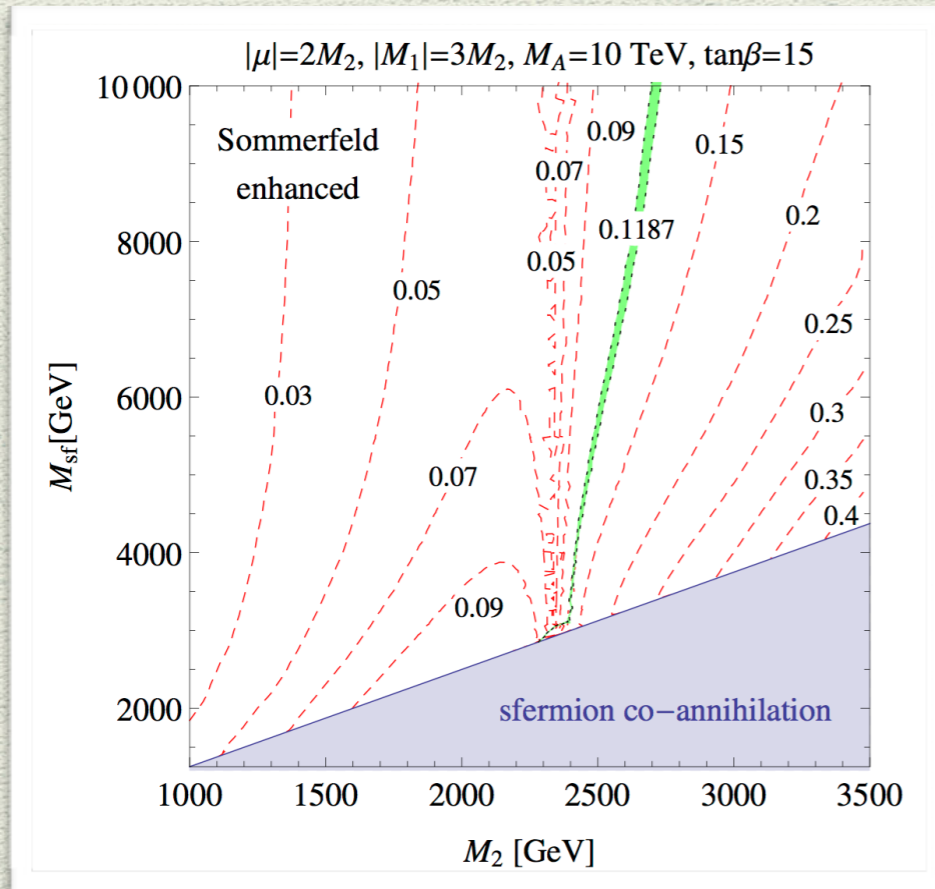
As the **sfermion** mass decreases the effective annihilation rate is suppressed due to **t-channel interference** - the correct relic abundance is obtained for masses of around 1.4 TeV\*

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

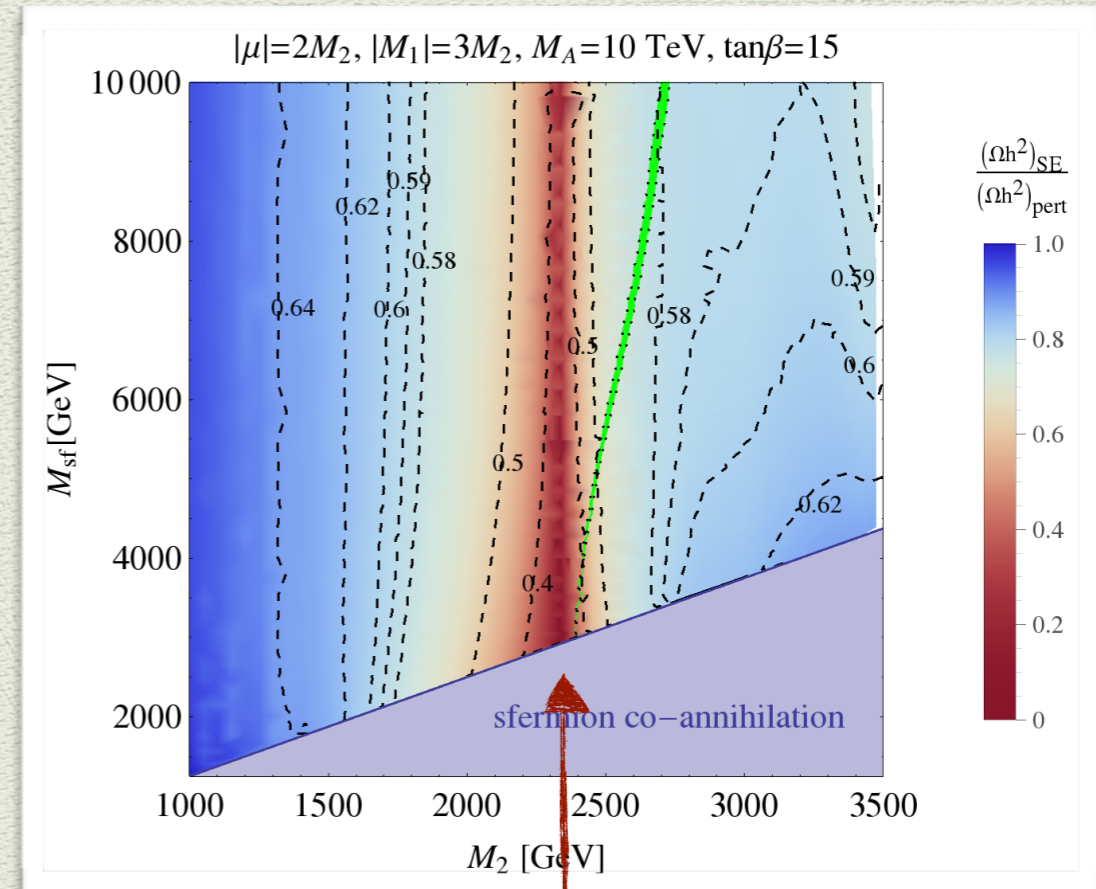
\*for the chosen set of parameters

# Results with Sommerfeld effect

## I) Wino with non-decoupled sfermions



The **correct relic density** is moved from 1.4-2.2 TeV up to 2.4-2.8 TeV



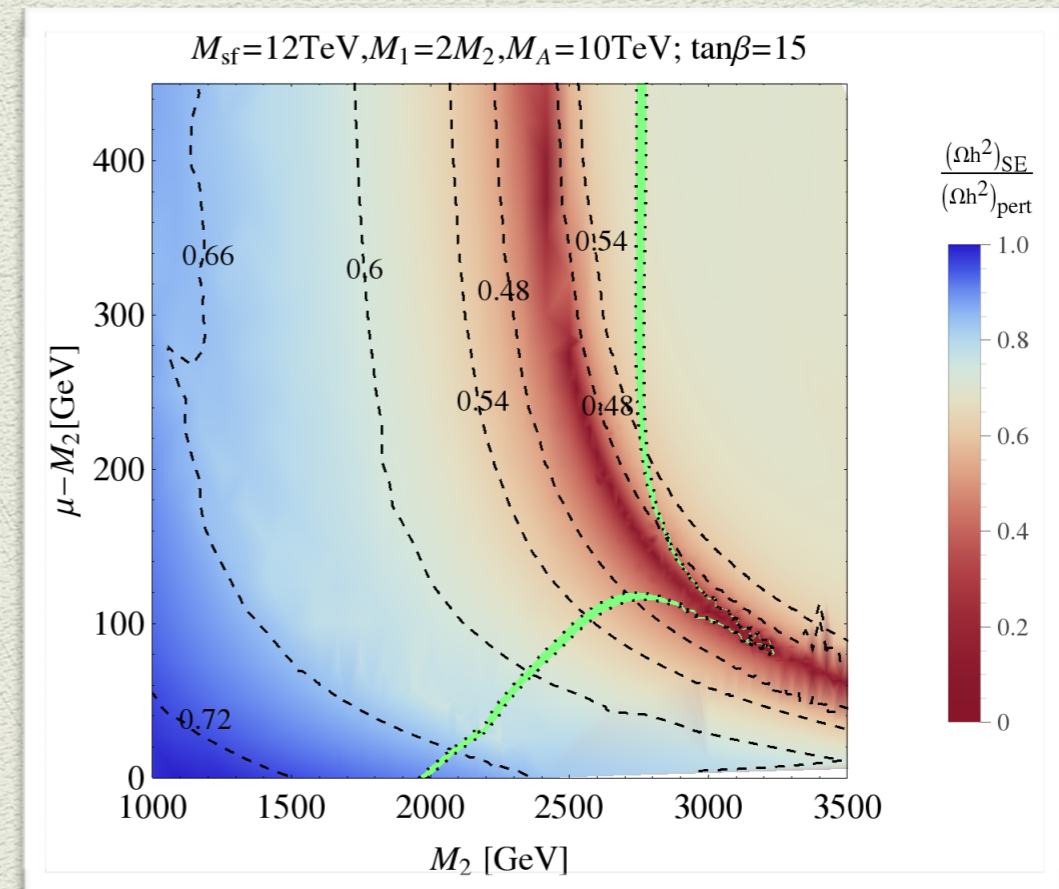
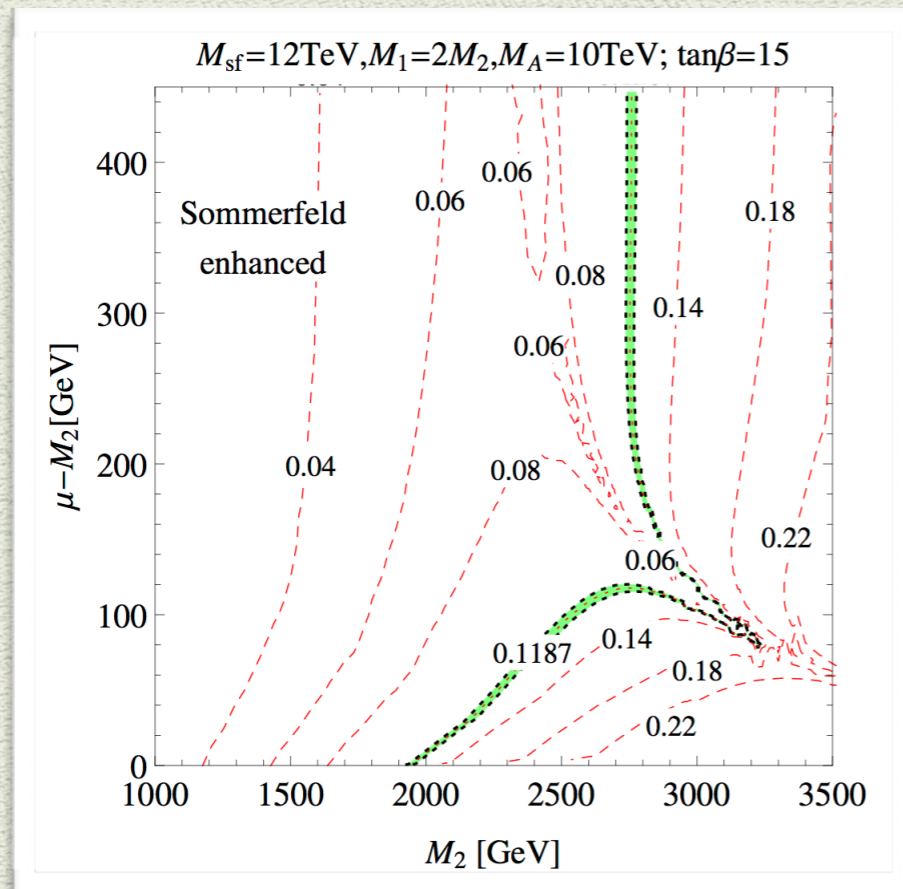
At 2.4 TeV **resonance** occurs, for low **sfermion** masses region with correct RD is resonant

Sommerfeld effect  $> O(30\%)$ , up to  $O(1)$  close to **resonance**



# Results with Sommerfeld effect

## II) Wino-higgsino admixture

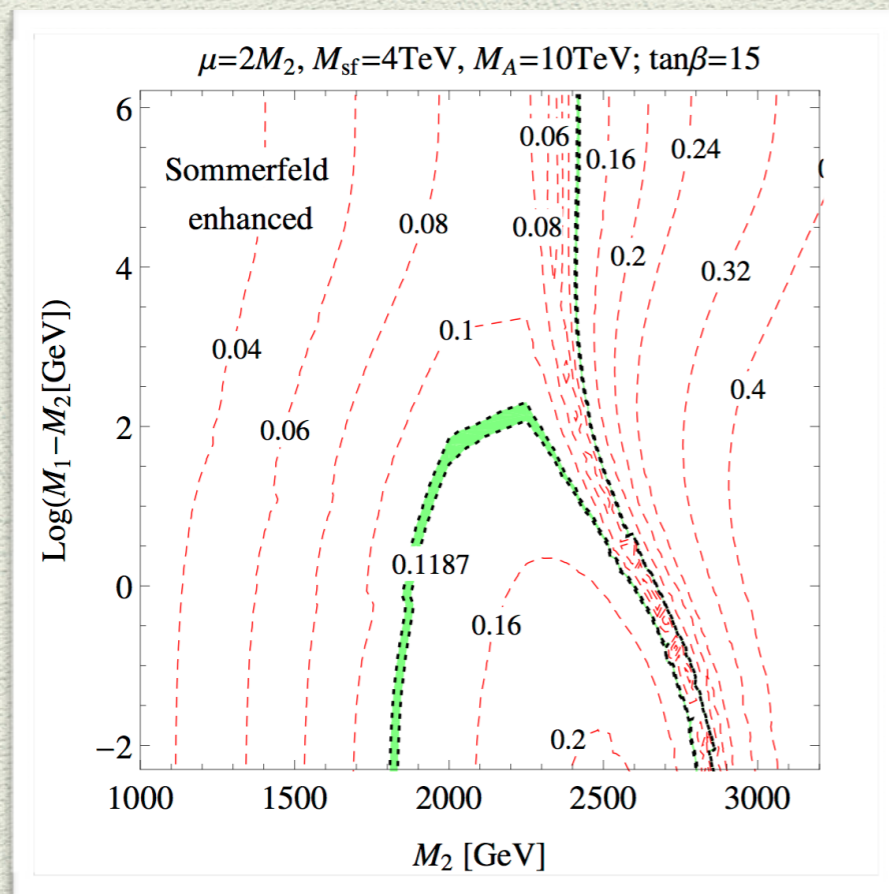


The **correct relic density** is moved from 1.7-2.2 TeV up to 1.9-3.3 TeV

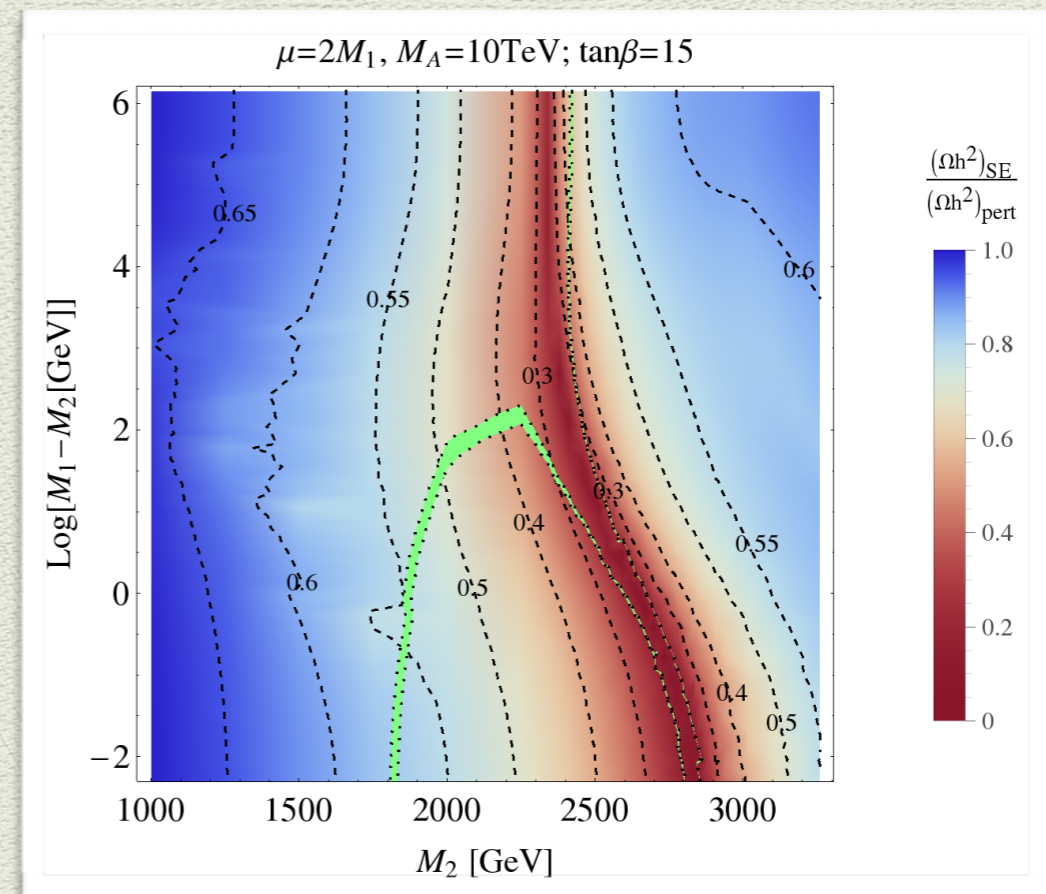
The position of the **resonance** is strongly  $\mu$ -dependent

# Results with Sommerfeld effect

## III) Wino-bino admixture



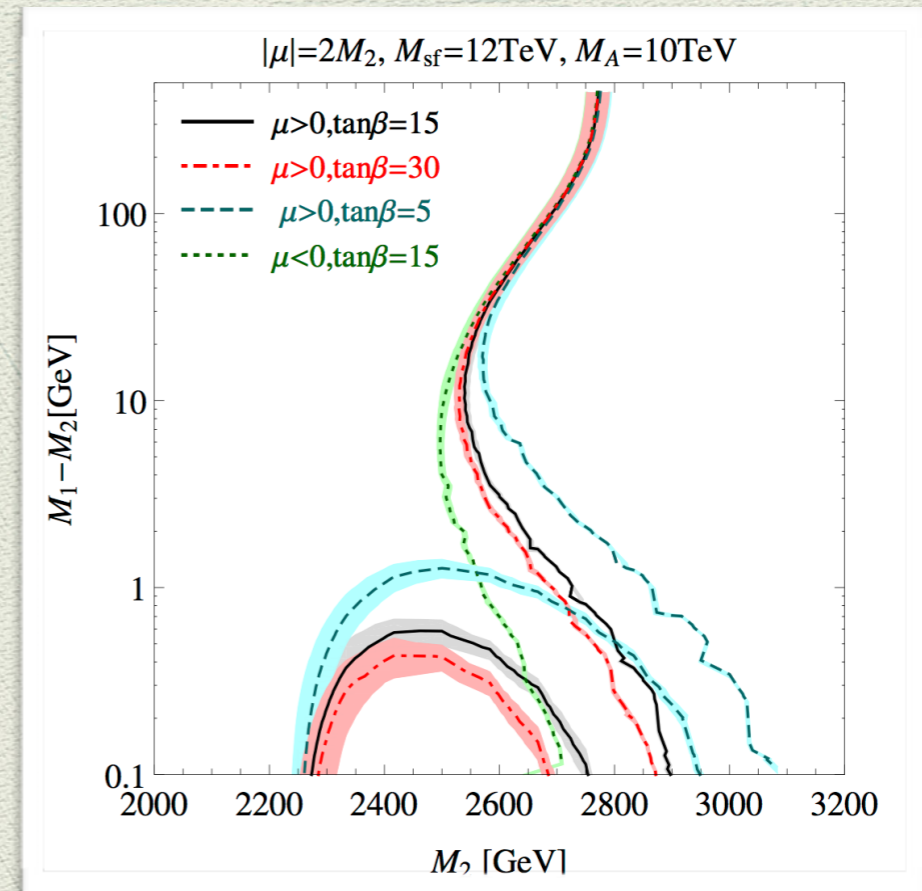
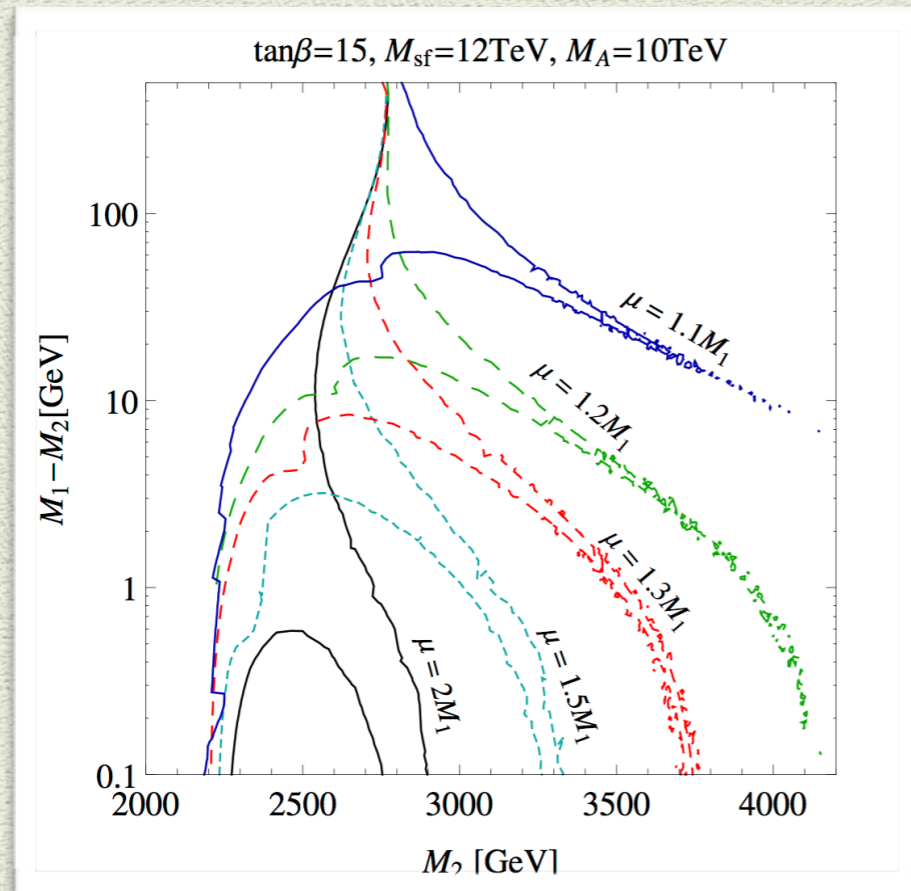
The **correct relic density** is moved from 1.5-1.8 TeV up to 1.8-2.9 TeV



The position of the **resonance** is strongly  $M_1$ -dependent

# Results with Sommerfeld effect

## III) Wino-bino admixture: dependence on residual parameters



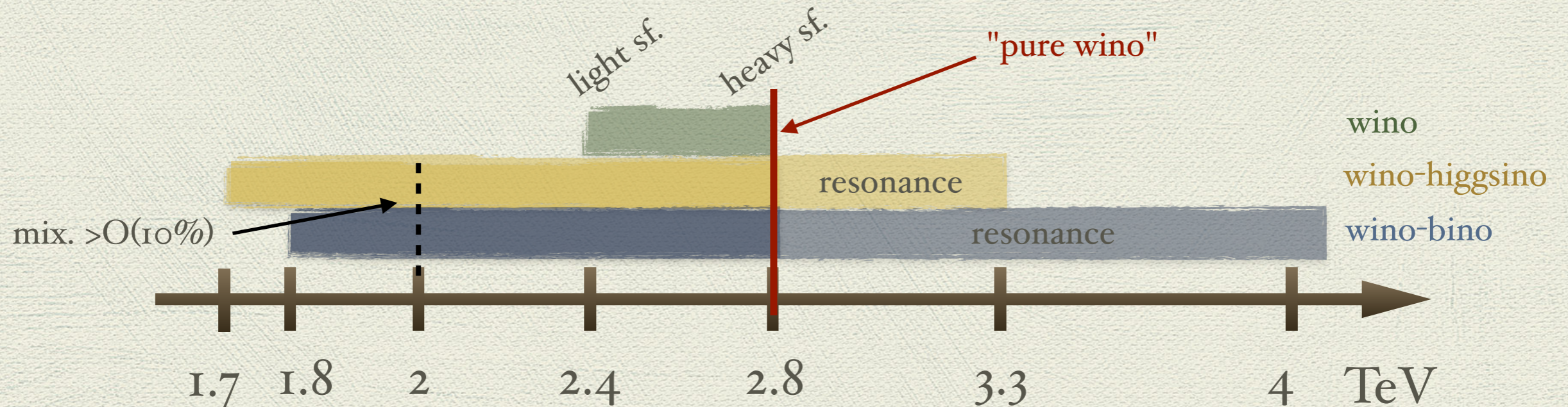
All contours have **correct relic density**

The position of the **resonance** strongly depends on the wino-bino mixing ( $\mu, \tan\beta$ )

# Conclusions

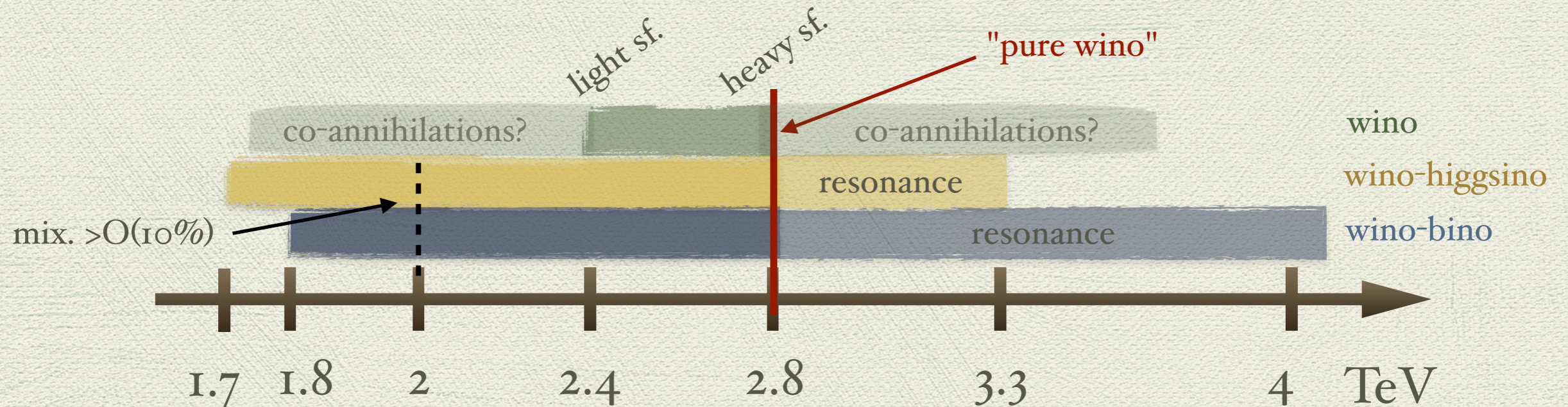
# Conclusions

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



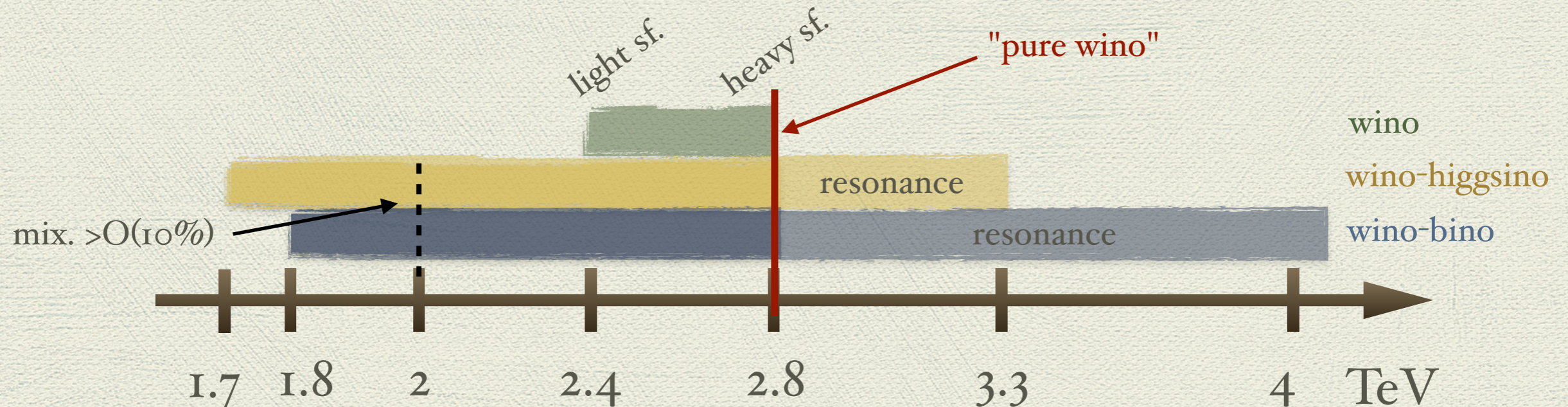
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# Conclusions

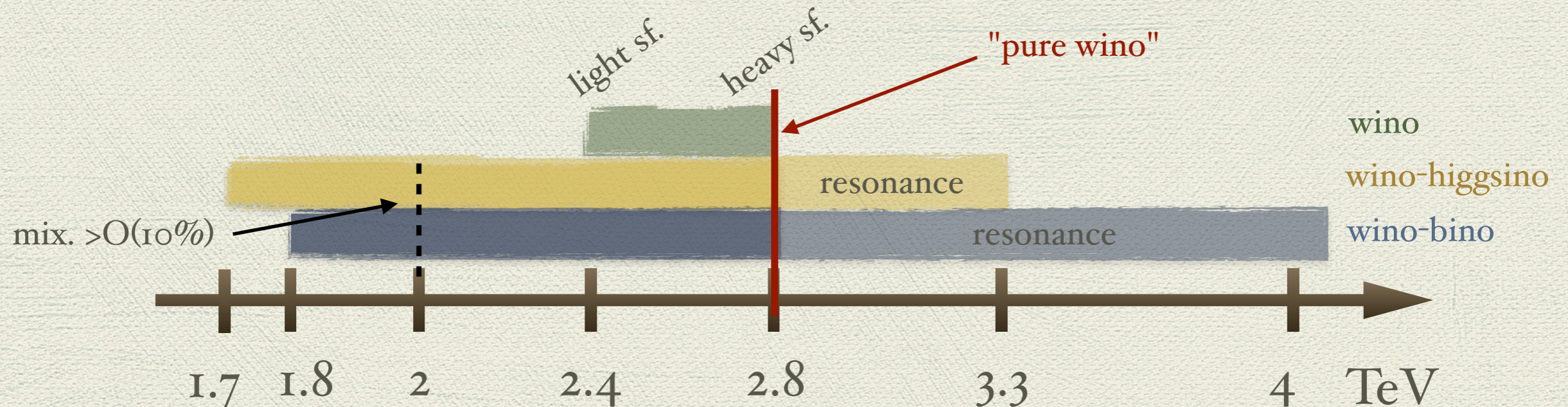
1. **Correct relic density** for wino-like neutralino in MSSM is obtained for wide range of masses:



2. SE effect  $> O(30\%)$  plus **resonance**  $\Rightarrow$  large ID signals  
(already constrained - work in progress...)

# Conclusions

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



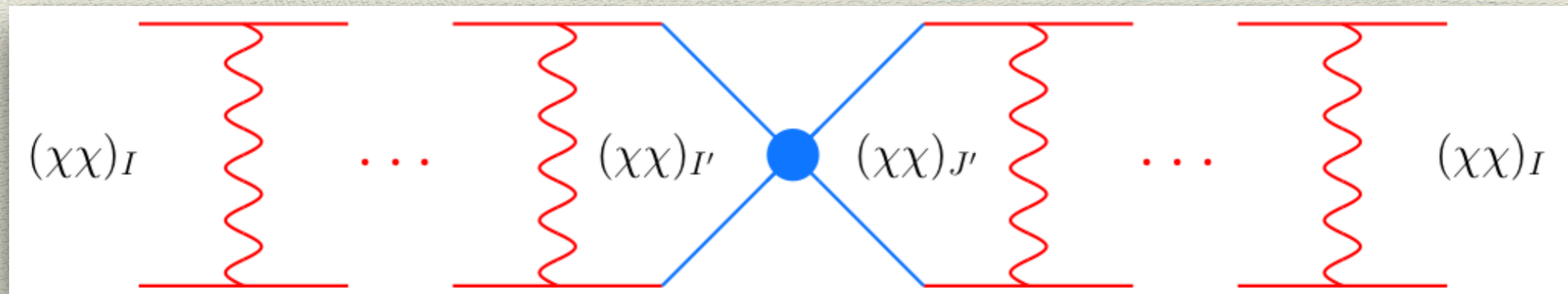
2. SE effect  $> O(30\%)$  plus **resonance**  $\Rightarrow$  large ID signals  
(already constrained - work in progress...)

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



Backup slides

Optical theorem + effective field theory lead to:



$$\sigma^{(\chi\chi)_I \rightarrow \text{light}} v_{\text{rel}} = \sum_{\text{wave}} S_I(\text{wave}) \hat{f}_{II}(\text{wave})$$

$$S_I = \frac{[\psi_{II'}]^* \hat{f}_{I'J'} [\psi_{J'I}]}{\hat{f}_{II}}$$

Long-range potential

- energy scale  $m_\chi v^2$
- non-perturbative effect
- solve a Schrödinger eq.

Short-range annihilation

- energy scale  $m_\chi$
- NR effective theory
- Wilson coeffs. of local operators
- off-diagonal reactions needed

# The Sommerfeld enhancement

## What is known?

- pure wino, pure higgsino

*Hisano et al. '04, '06*

- mixed wino-higgsino (with everything else decoupled)

*Hryczuk et al. '11, Beneke et al. '14*

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- gluino co-annihilation

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- Minimal DM model

*Cirelli et al. '07, '08, '09*

Only available tool for the MSSM:

**DarkSE package**

*Hryczuk, '11*

# The Sommerfeld enhancement

New 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
- present day annihilation in the halo (for ID)
- accuracy at  $O(\%)$ , dominated by theoretical uncertainties of EFT

└─> caveat: still no NLO effects...

# Parameter ranges

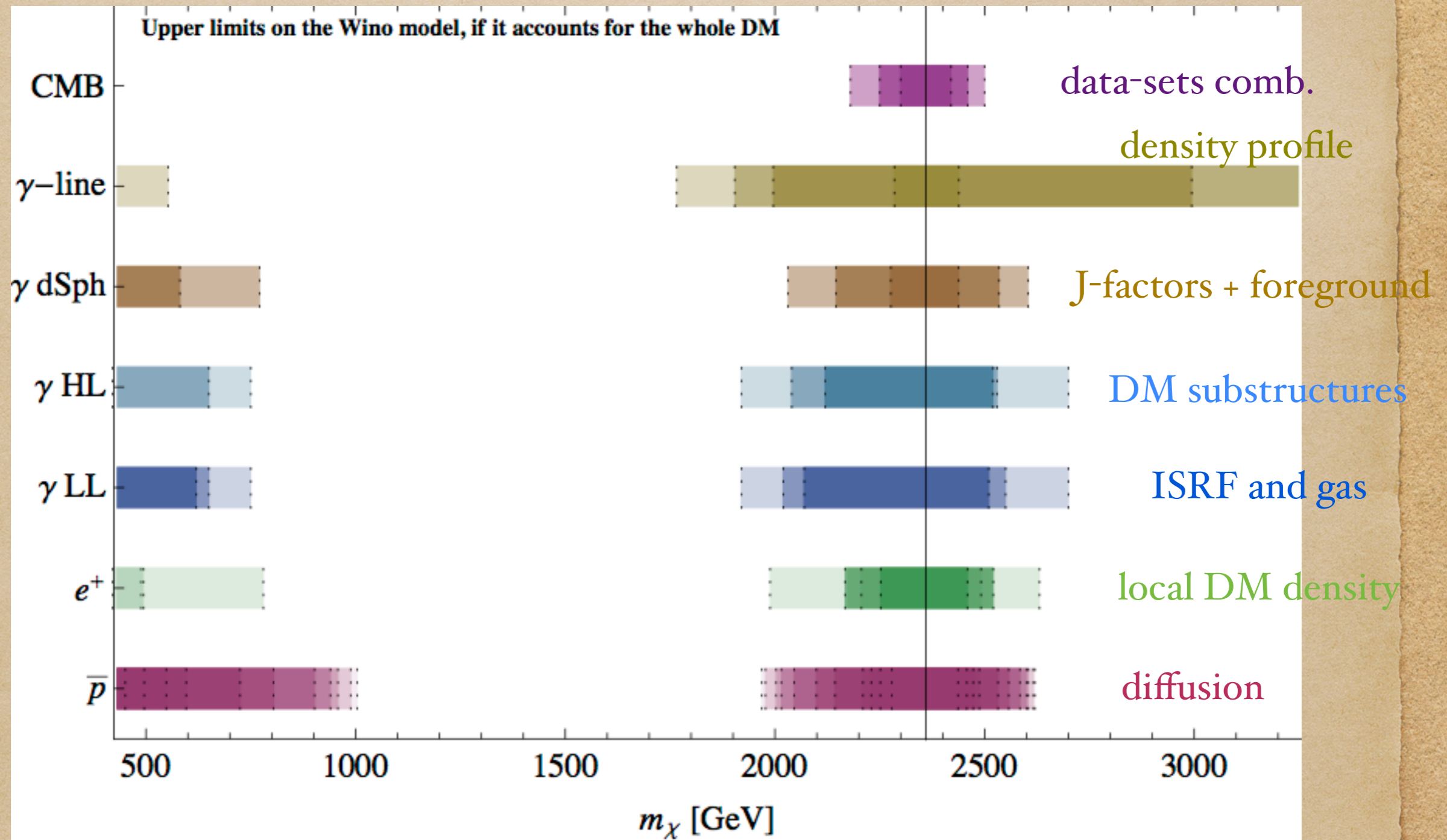
Parameter	Range
$M_2$ $ \mu  - M_2$ $ M_1  - M_2$ $M_{sf}$	1 - 5 TeV 0 - 500 GeV 0 - 500 GeV $1.25 M_2 - 12 \text{ TeV}$
$ A_f $ $\tan \beta$	1 - 10 TeV 5 - 30
$M_{A^0}$ $M_3$	0 - 8 TeV $1.25 M_2 - 8 \text{ TeV}$

**Central parameters**  
 wino-like LSP mass  
 higgsino and bino fractions  
 common sfermion mass

Residual parameters

# LIMITS ON WINO DM

## UNCERTAINTIES



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