

Relic density of wino-like dark matter in the MSSM

Francesco Dighera



Technische Universität München

In collaboration with:

M. Beneke, A. Bharucha, C. Hellmann, A. Hryczuk,

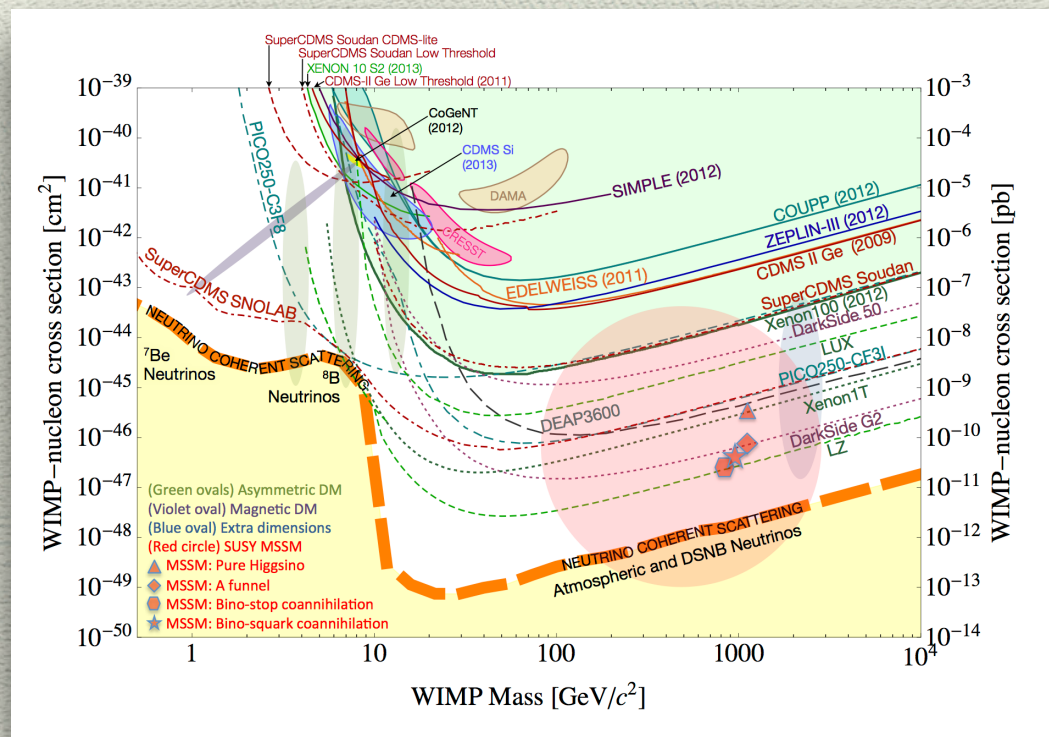
S. Recksiegel and P. Ruiz-Femenia

to appear soon...

Motivations

Motivations

Why heavy neutralinos as dark matter?



ATLAS SUSY Searches* - 95% CL Lower Limits					ATLAS Preliminary			
Status: July 2015					$\sqrt{s} = 7, 8 \text{ TeV}$			
Model	$\epsilon, \mu, \tau, \gamma$	Jets	$E_{\text{miss}}^{\text{min}}$	$\int L d\tau [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$	Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ, τ	2-10 jets	Yes	20.3	100-440 GeV	850 GeV	1507.05525
	$\tilde{q}\tilde{q} \rightarrow q\tilde{q}\tilde{g}$	0	2-6 jets	Yes	20.3	100-440 GeV	850 GeV	1465.7675
	$\tilde{q}\tilde{q} \rightarrow q\tilde{q}\tilde{g}$ (compressed)	0	mono-jet	1-3 jets	Yes	20.3	100-440 GeV	1507.05525
	$\tilde{q}\tilde{q} \rightarrow q\tilde{q}\tilde{g}$ ($\ell\ell\nu\nu$)	2 e, μ (off-Z)	2 jets	Yes	20.3	100-440 GeV	780 GeV	1503.05290
	$\tilde{g}\tilde{g} \rightarrow g\tilde{g}\tilde{g}$	0	2-6 jets	Yes	20.3	100-440 GeV	1.23 TeV	1465.7675
	$\tilde{g}\tilde{g} \rightarrow g\tilde{g}\tilde{g}$ ($\ell\ell\nu\nu$)	0-1 e, μ	2-6 jets	Yes	20.2	100-440 GeV	1.32 TeV	1507.05525
	$\tilde{g}\tilde{g} \rightarrow g\tilde{g}\tilde{g}$ ($\ell\ell\nu\nu$)	2 e, μ	0-3 jets	-	20.2	100-440 GeV	1.32 TeV	1501.03555
	GMSB (\tilde{L} NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	100-440 GeV	1.26 TeV	1507.05525
	GGM (bino NLSP)	2 γ	2 jets	Yes	20.3	100-440 GeV	1.29 TeV	1507.05525
	GGM (higgsino-bino NLSP)	2 γ	1 b	Yes	20.3	100-440 GeV	1.3 TeV	1507.05525
	GGM (higgsino-bino NLSP)	2 γ	2 jets	Yes	20.3	100-440 GeV	1.25 TeV	1507.05525
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	100-440 GeV	1.25 TeV	1503.02090
GraVino LSP	0	mono-jet	Yes	20.3	100-440 GeV	865 GeV	1502.01518	
$\tilde{g}\tilde{g}$ prod. & med.	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{g}$	0	3 b	Yes	20.1	100-440 GeV	1.26 TeV	1407.06000
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{g}$	0	7-10 jets	Yes	20.3	100-440 GeV	1.1 TeV	1308.1841
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{g}$	0-1 e, μ	3 b	Yes	20.1	100-440 GeV	1.34 TeV	1407.06000
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{g}$	0-1 e, μ	3 b	Yes	20.1	100-440 GeV	1.3 TeV	1407.06000
$\tilde{g}\tilde{g}$ prod. & direct	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{g}$	0	2 b	Yes	20.1	100-440 GeV	100-820 GeV	1308.2631
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{g}$	2 e, μ (SS)	0-3 b	Yes	20.3	100-440 GeV	275-440 GeV	1404.25500
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{g}$	1-2 e, μ	1-2 b	Yes	4.7/20.3	100-440 GeV	230-460 GeV	1209.2102, 1407.0593
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{g}$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3	100-440 GeV	90-191 GeV	1506.08616
EW direct	$\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$	2 e, μ	0	Yes	20.3	100-440 GeV	90-240 GeV	1407.06000
	$\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$	2 e, μ	0	Yes	20.3	100-440 GeV	150-580 GeV	1403.5222
	$\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$	2 e, μ	0	Yes	20.3	100-440 GeV	290-600 GeV	1403.5222
	$\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$	2 e, μ	0	Yes	20.3	100-440 GeV	90-325 GeV	1403.5222
Long-lived particles	Direct $\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$ prod., long-lived \tilde{t}	Disapp. trk	1 jet	Yes	20.3	270 GeV	482 GeV	1310.3675
	Direct $\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$ prod., long-lived \tilde{t}	dE/dx trk	-	Yes	18.4	270 GeV	482 GeV	1506.05332
	Stable, stopped \tilde{t} R-hadron	0	1-5 jets	Yes	27.9	270 GeV	832 GeV	1310.6584
	Stable \tilde{t} R-hadron	trk	-	-	19.1	270 GeV	1.27 TeV	1411.6795
	GMSB, stable \tilde{t} , $\tilde{t} \rightarrow \tilde{t} + \tilde{t} + \tilde{t} + \tilde{t} + \tilde{t}$	1-2 μ	-	-	19.1	270 GeV	537 GeV	1411.6795
	GMSB, $\tilde{t} \rightarrow \tilde{t} + \tilde{t} + \tilde{t} + \tilde{t} + \tilde{t}$	2 γ	-	Yes	20.3	270 GeV	435 GeV	1409.5542
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{g}$	displ. $e\ell/g\ell/\mu\mu$	-	-	20.3	270 GeV	1.0 TeV	1504.05162
	$\tilde{g}\tilde{g} \rightarrow b\tilde{b}\tilde{g}$	displ. $\nu\bar{\nu} + \text{jets}$	-	-	20.3	270 GeV	1.0 TeV	1504.05162
	LFV $\tilde{g}\tilde{g} \rightarrow \tilde{t}\tilde{t} + \tilde{X}_0 \rightarrow q\ell\ell/\mu\tau$	$e\ell, e\mu, \tau\tau$	-	-	20.3	270 GeV	1.7 TeV	1503.04430
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	270 GeV	1.35 TeV	1404.25500
	$\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$	4 e, μ	Yes	20.3	2	270 GeV	750 GeV	1405.5086
	$\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$	3 $e, \mu + \tau$	Yes	20.3	2	270 GeV	450 GeV	1405.5086
RPV	$\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$	0	6-7 jets	-	20.3	270 GeV	817 GeV	1502.05696
	$\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$	0	6-7 jets	-	20.3	270 GeV	970 GeV	1502.05696
	$\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$	2 e, μ (SS)	0-3 b	Yes	20.3	270 GeV	850 GeV	1502.05696
	$\tilde{t}\tilde{t} \rightarrow b\tilde{b}\tilde{g}$	2 e, μ	2 jets + 2 b	-	20.3	270 GeV	100-308 GeV	1404.250
Other	Scalar charm, $\tilde{c} \rightarrow \tilde{c}^0$	0	2 c	Yes	20.3	270 GeV	490 GeV	1501.01325
							$m(\tilde{t}_1) > 200 \text{ GeV}$	1501.01325

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

Motivations

Why precision calculations are needed?

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

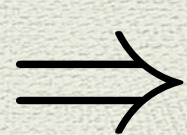
Planck + lensing + BAO, '15



uncertainty < 1%*

* does not change much
when varying experimental
data combinations

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



theoretical uncertainty
significantly larger!

loop corrections

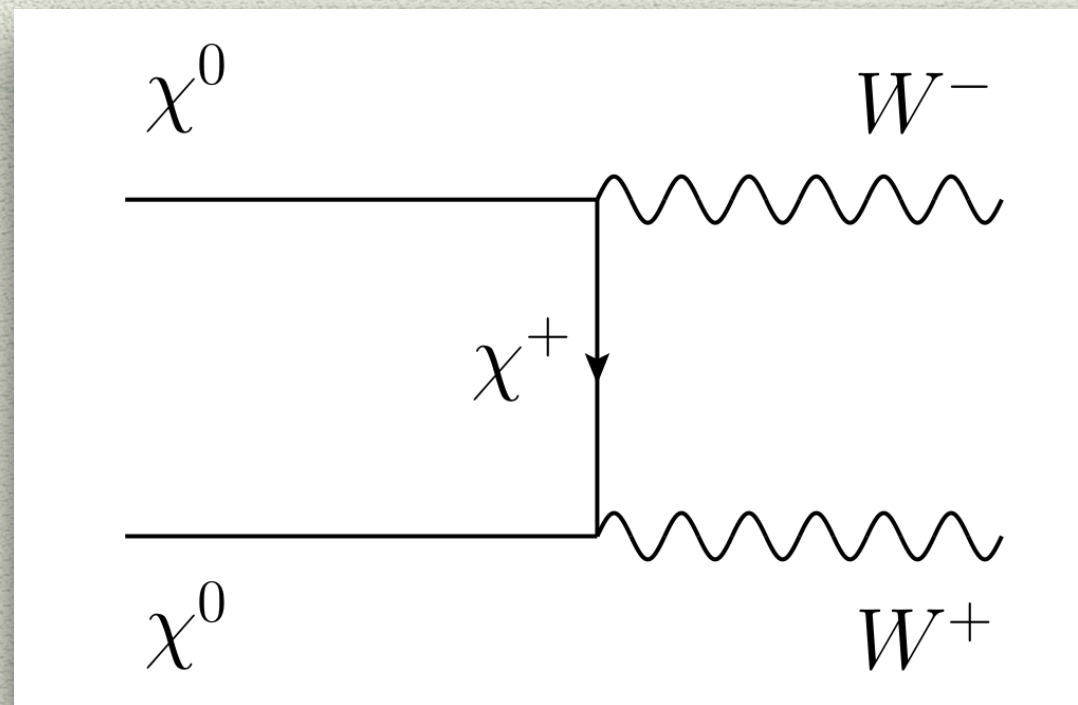
LL resummation
Sommerfeld enhancement

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

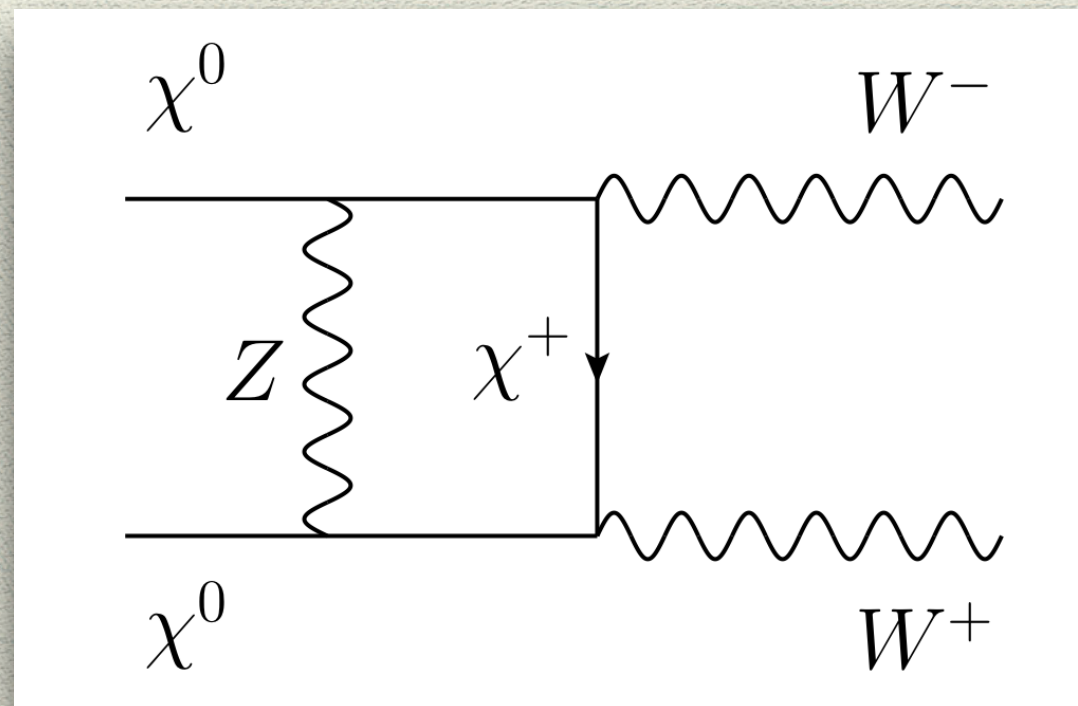
The Sommerfeld enhancement

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

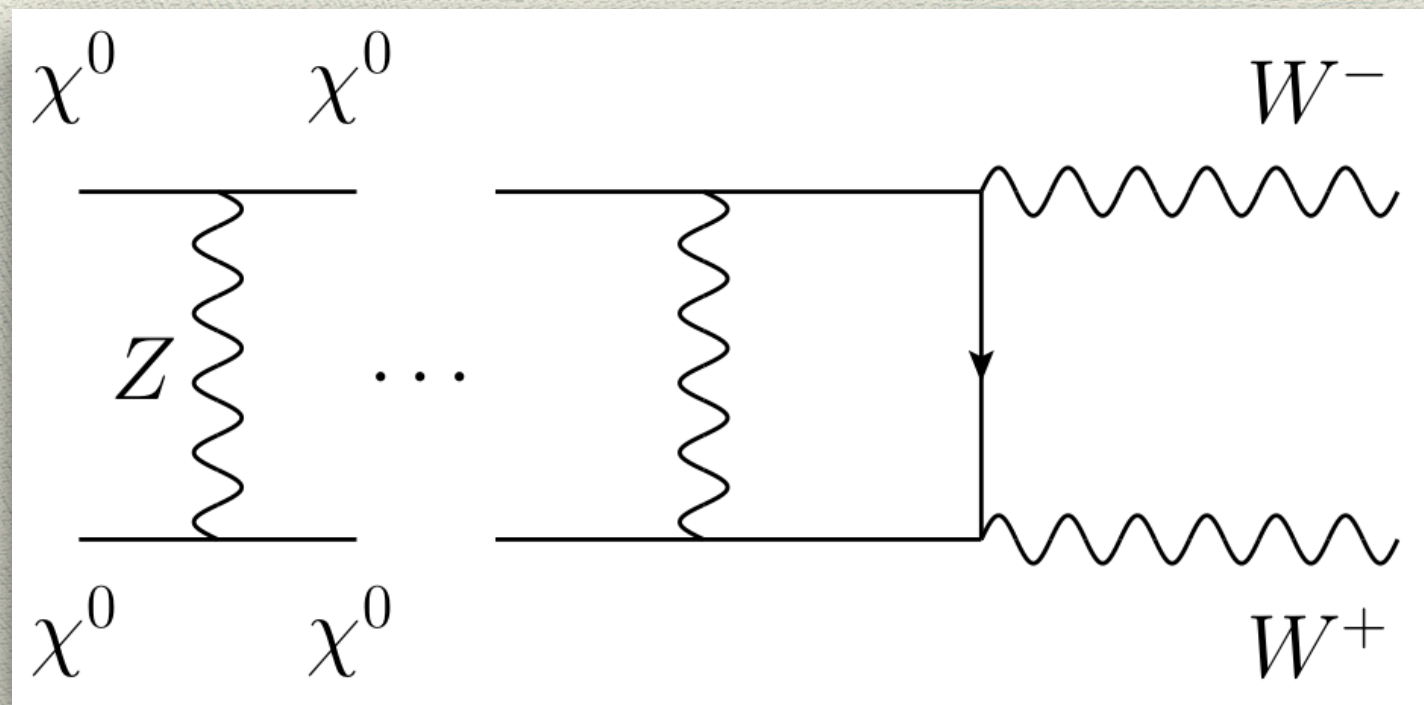
Low mediator mass: $\frac{1}{m_Z} \gtrsim \frac{1}{\alpha m_\chi}$
force range Bohr radius

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

O(1), no suppression!

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

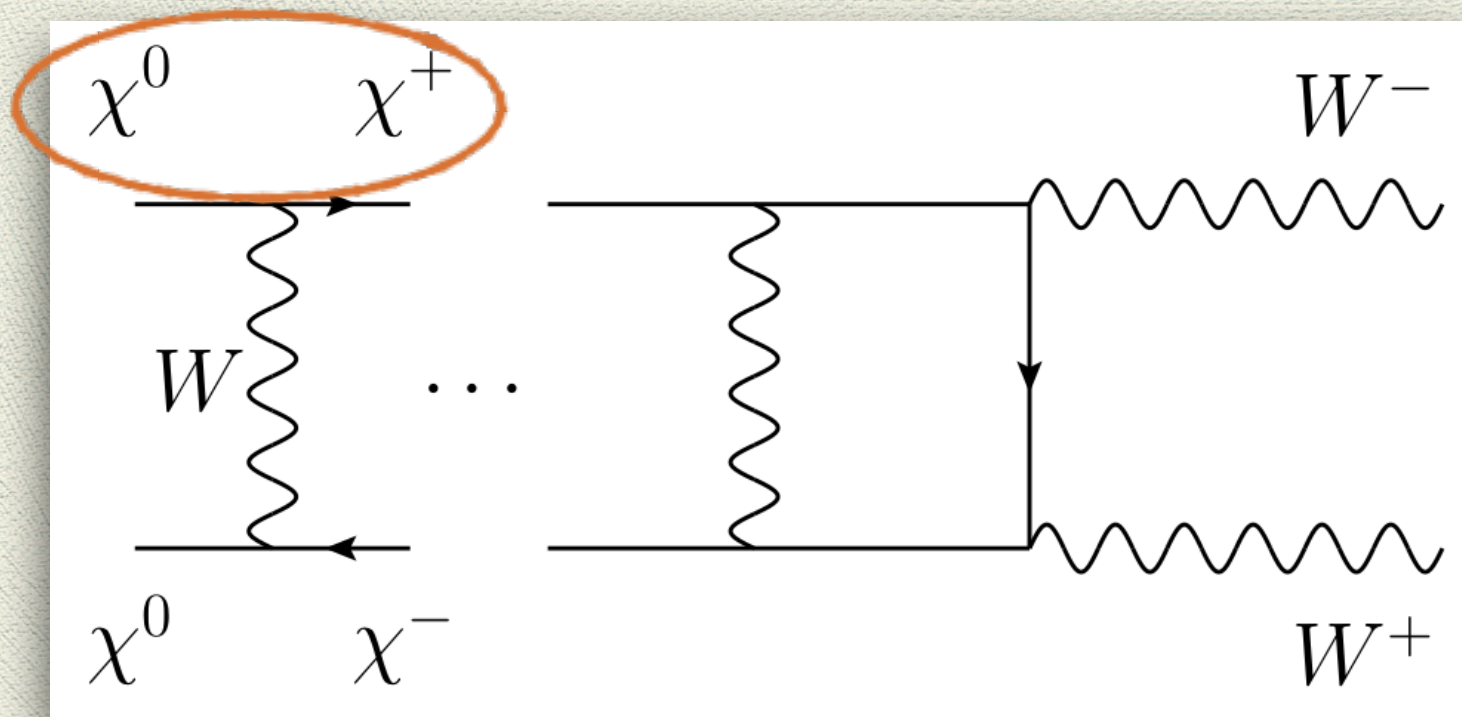
\Rightarrow **resummation** of ladder diagrams is needed!



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

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

\Rightarrow **resummation** of ladder diagrams is needed!



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

Not included here → • stop and stau co-annihilations

Freitas '07, Hryczuk '11, Klasen et al. '14

here

→ • gluino co-annihilation

Ellis et al. '15

• Minimal DM model

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

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

Not included here → • stop and stau co-annihilations

Freitas '07, Hryczuk '11, Klasen et al. '14

here

→ • gluino co-annihilation

Ellis et al. '15

• Minimal DM model

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

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 $O(10\%)$

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

Not included here → • stop and stau co-annihilations

Freitas '07, Hryczuk '11, Klasen et al. '14

here

→ • gluino co-annihilation

Ellis et al. '15

• Minimal DM model

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

2. Sommerfeld effect for P- and $O(v^2)$ S-wave

3. Off-diagonal annihilation matrices

← not present in DarkSE *Hryczuk, '11*

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

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

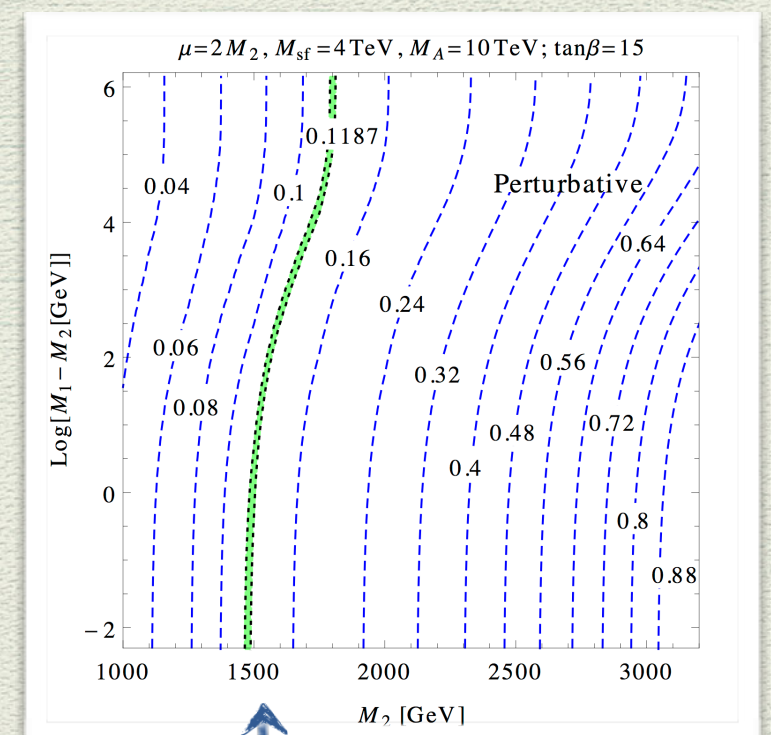
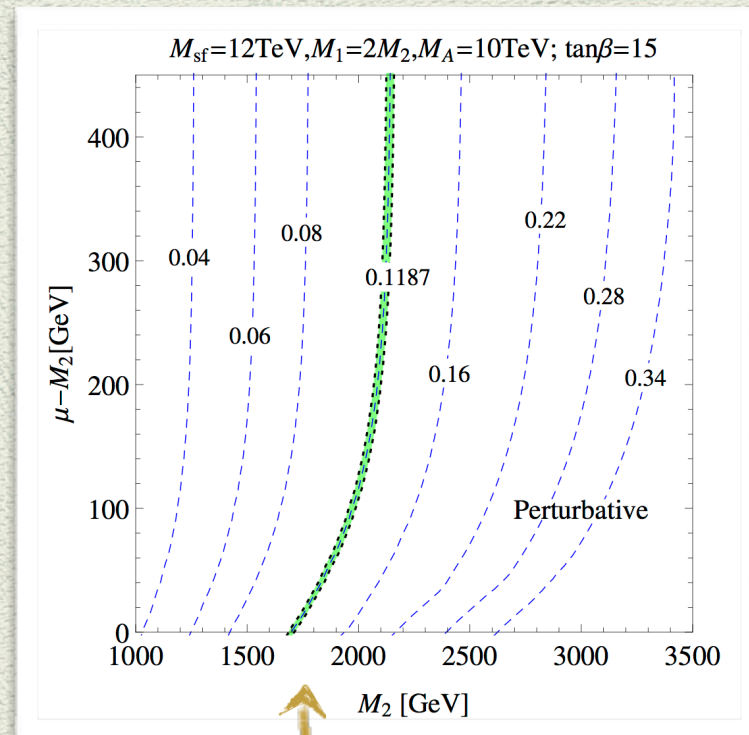
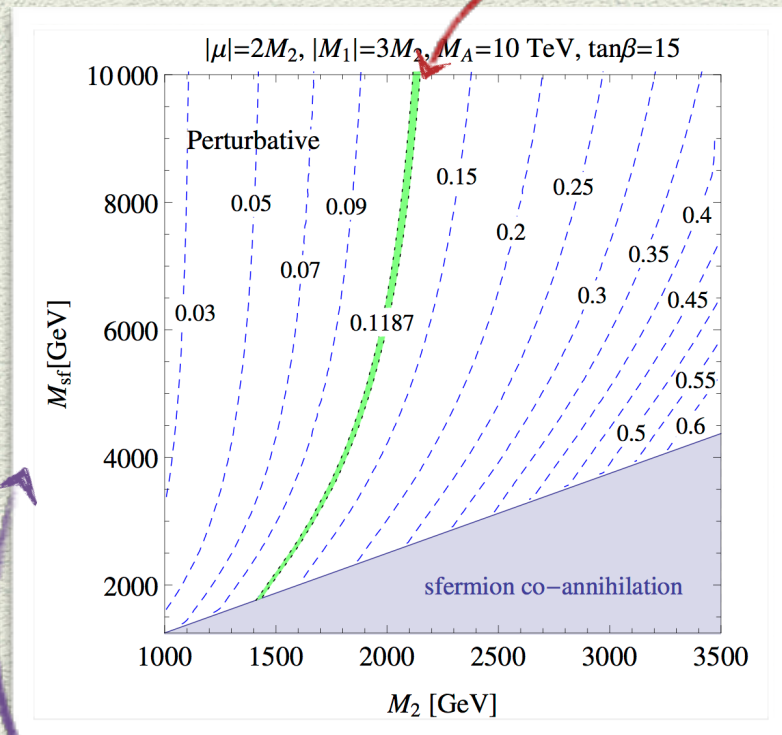
5. Accuracy at $O(\%)$ (NLO still missing...)

Results

Tree level results

Wino-like neutralino with higgsino or bino admixtures

"pure wino" 2.2 TeV



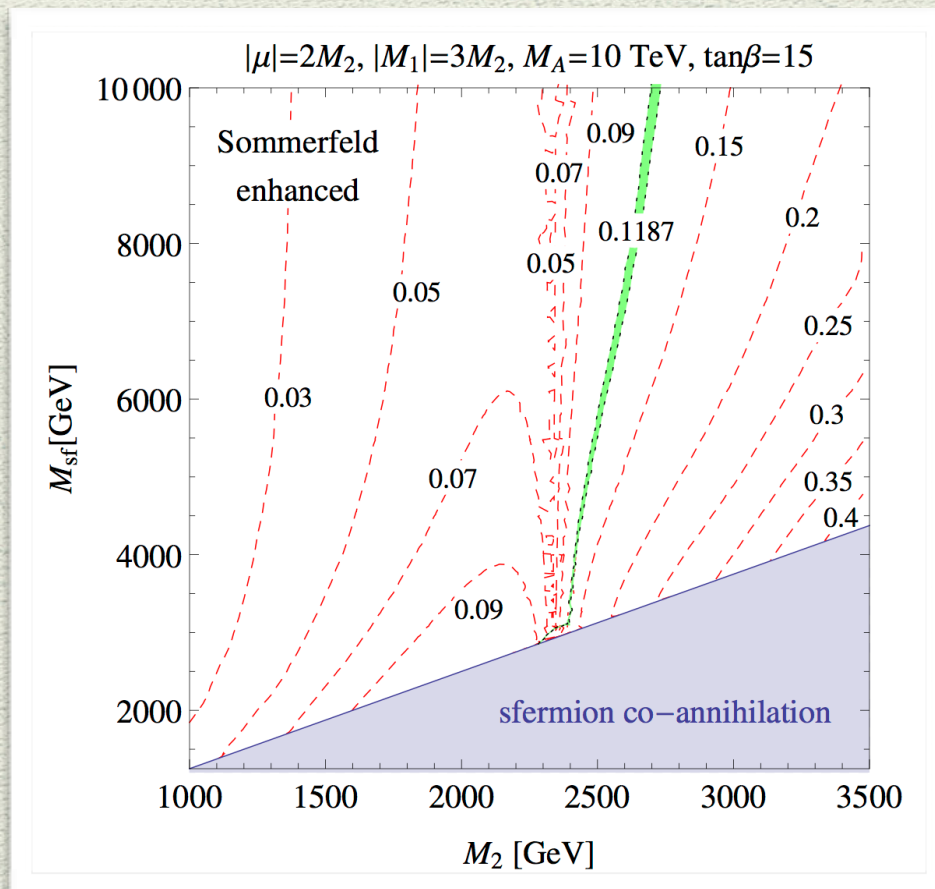
As the **sfermion** mass decreases the effective annihilation rate is suppressed due to **t-channel interference** - the correct relic abundance is obtained for masses of around 1.4 TeV*

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

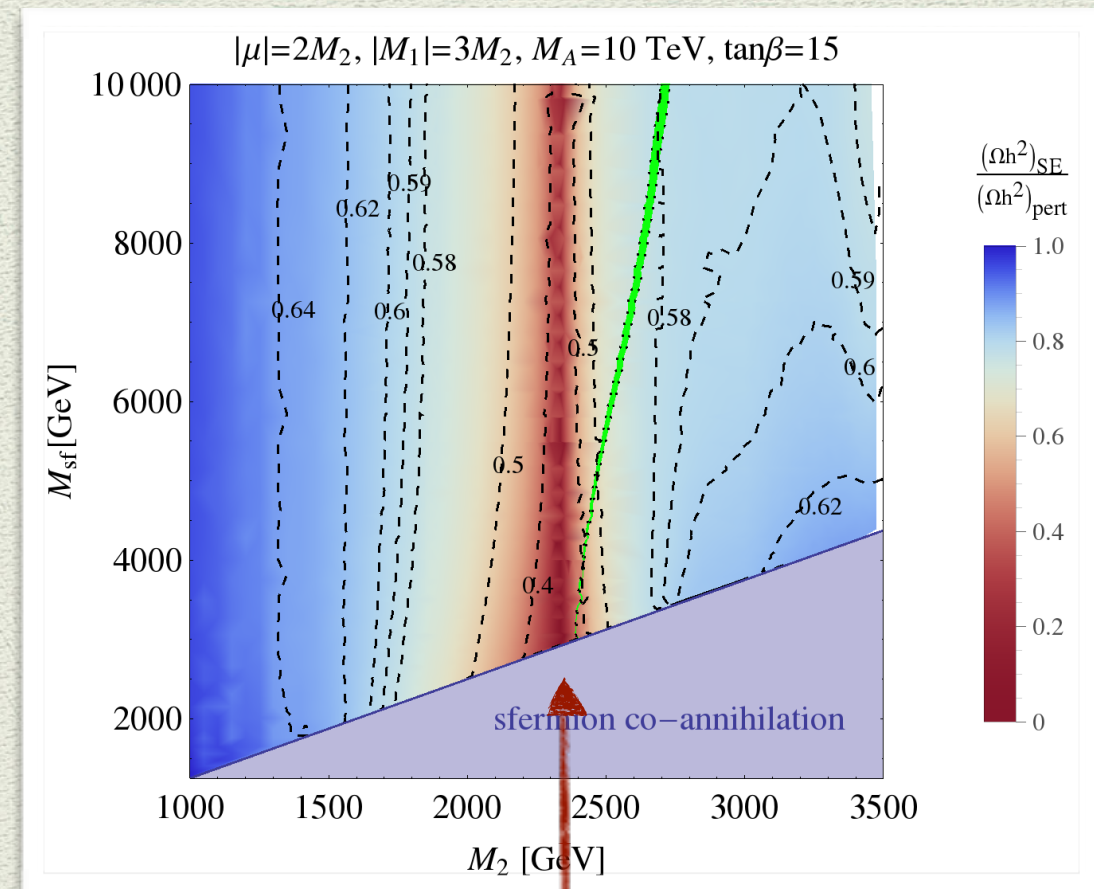
*for the chosen set of parameters

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

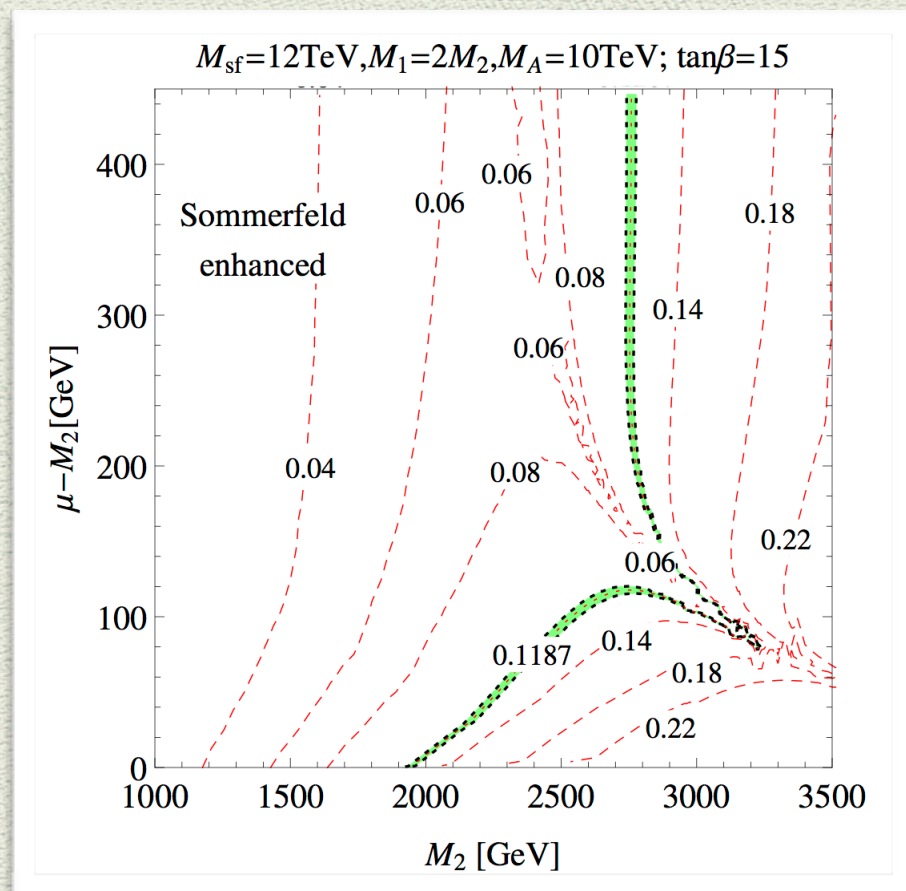


At 2.4 TeV **resonance** occurs, for low **sfermion** masses region with correct RD is resonant

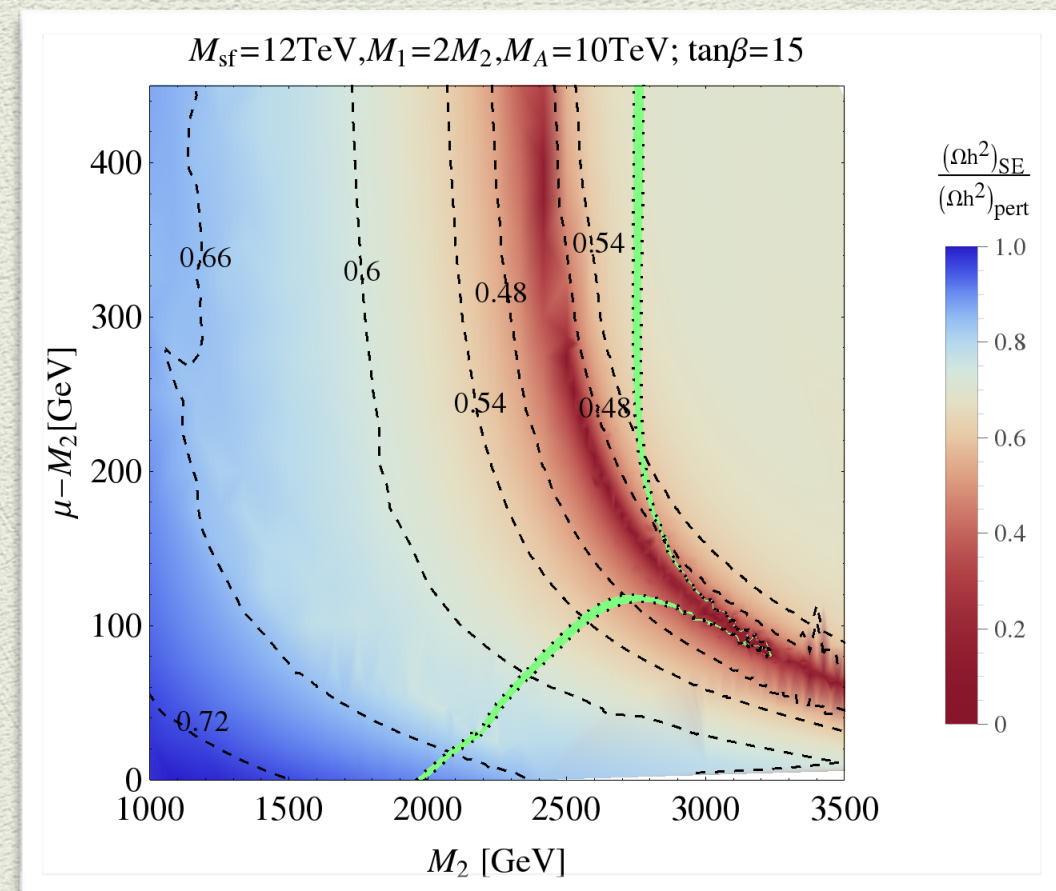
Sommerfeld effect $> O(30\%)$, up to $O(1)$ close to **resonance**

Results with Sommerfeld effect

II) Wino-higgsino admixture



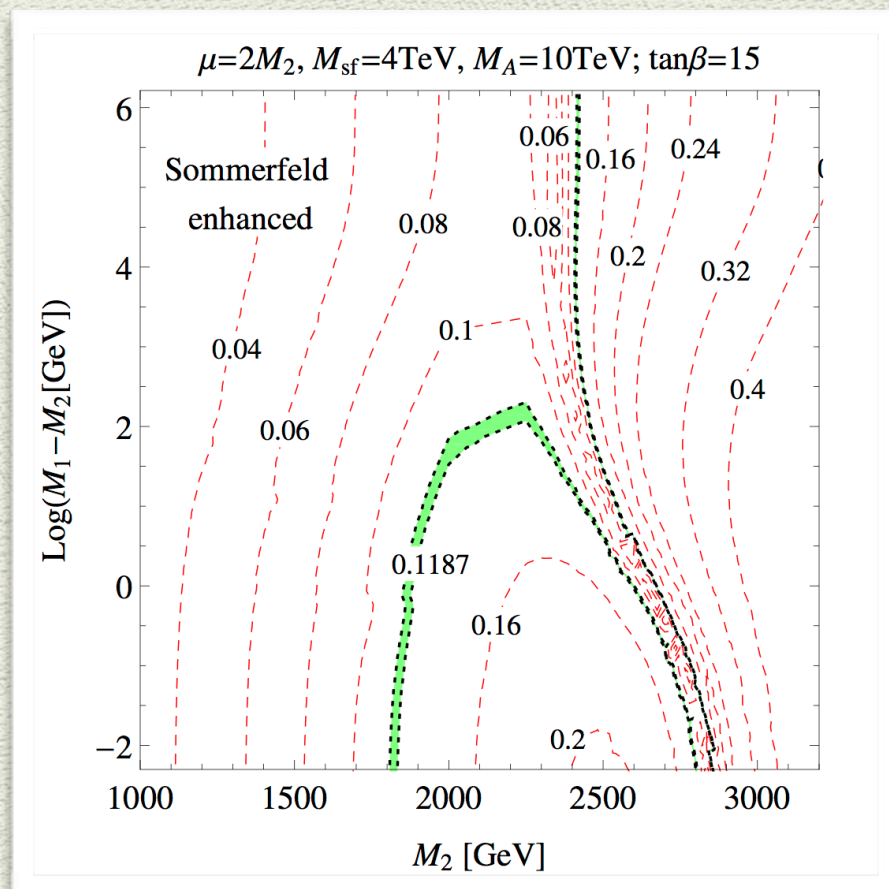
The **correct relic density** is moved from 1.7-2.2 TeV up to 1.9-3.3 TeV



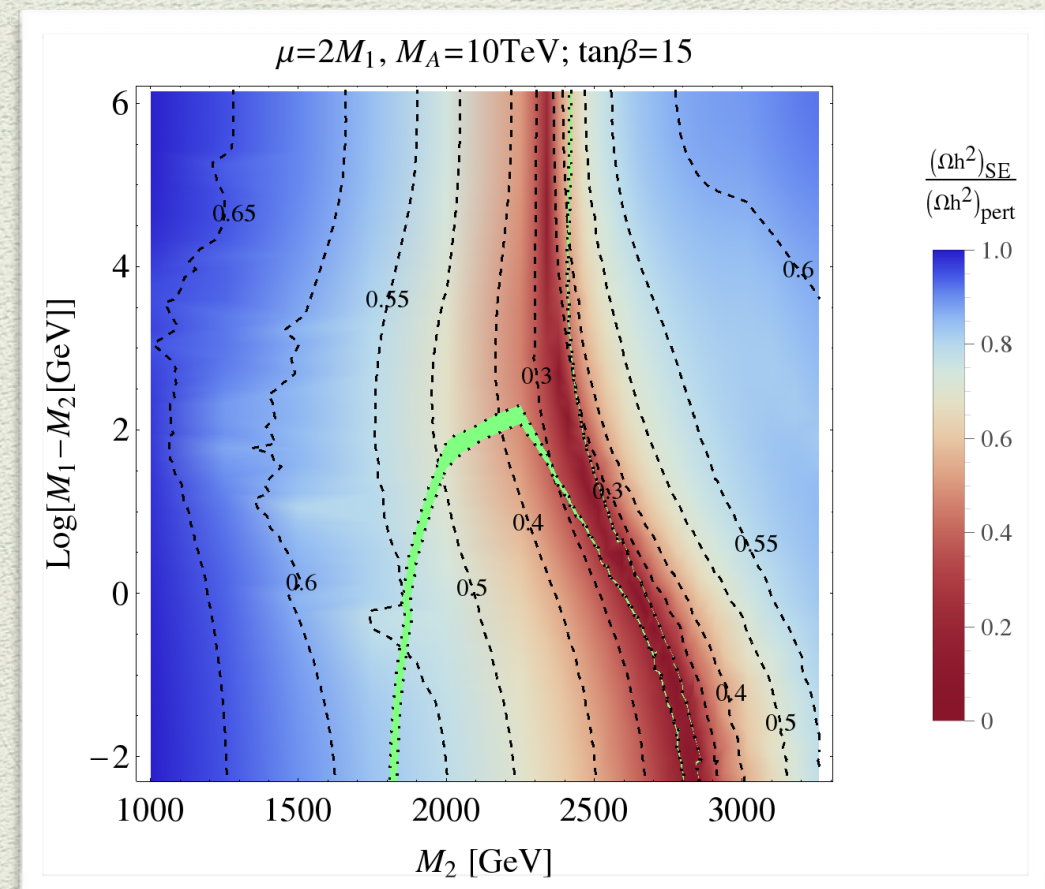
The position of the **resonance** is strongly μ -dependent

Results with Sommerfeld effect

III) Wino-bino admixture



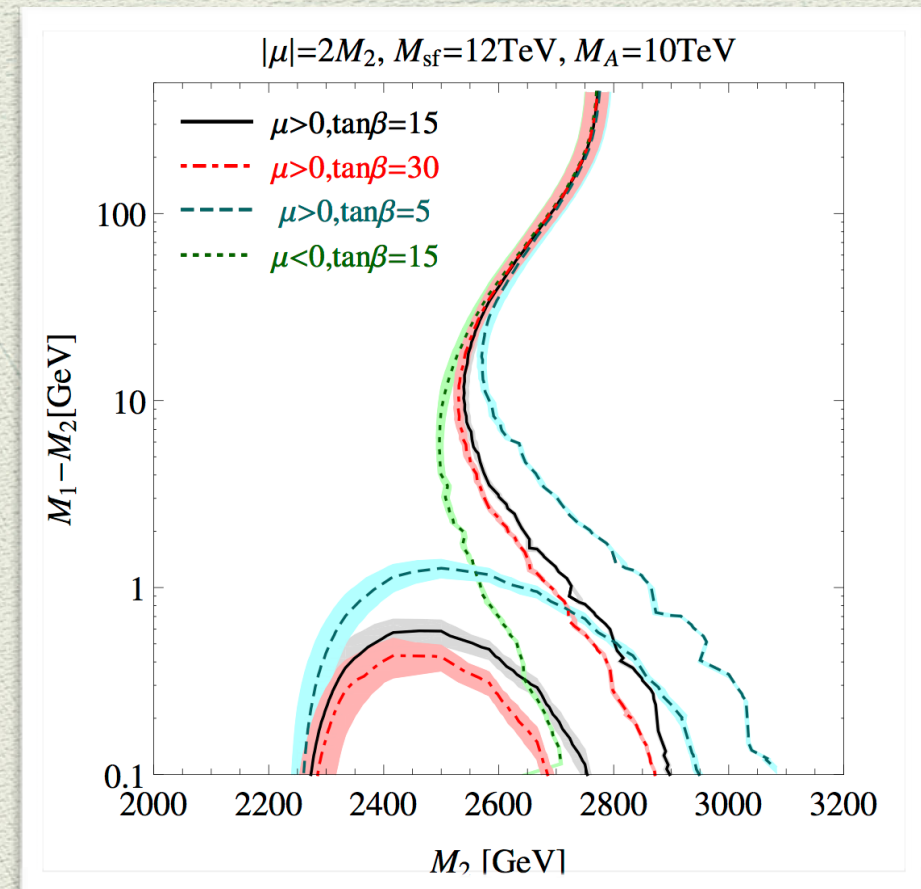
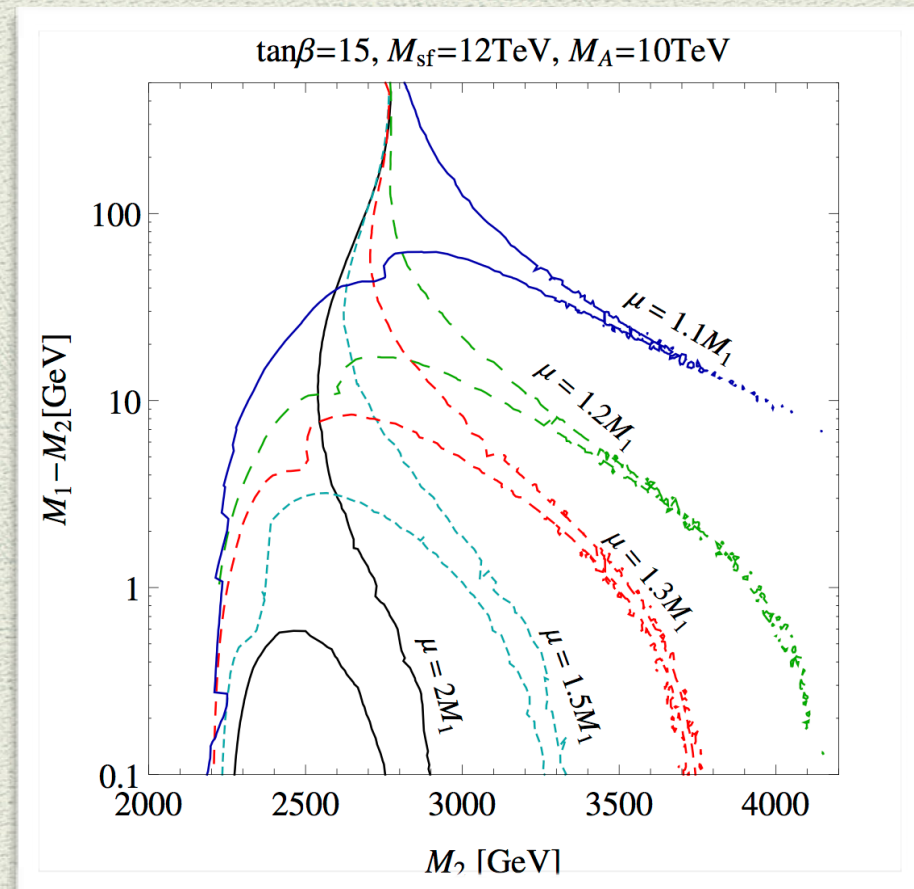
The **correct relic density** is moved from 1.5-1.8 TeV up to 1.8-2.9 TeV



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

Results with Sommerfeld effect

III) Wino-bino admixture: dependence on residual parameters



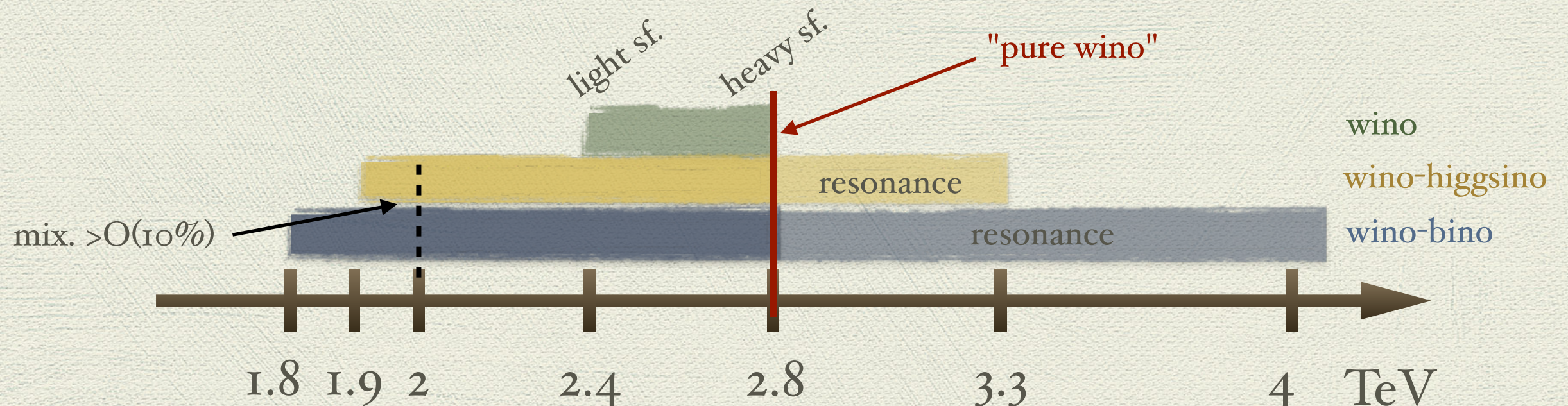
All contours have **correct relic density**

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

Conclusions

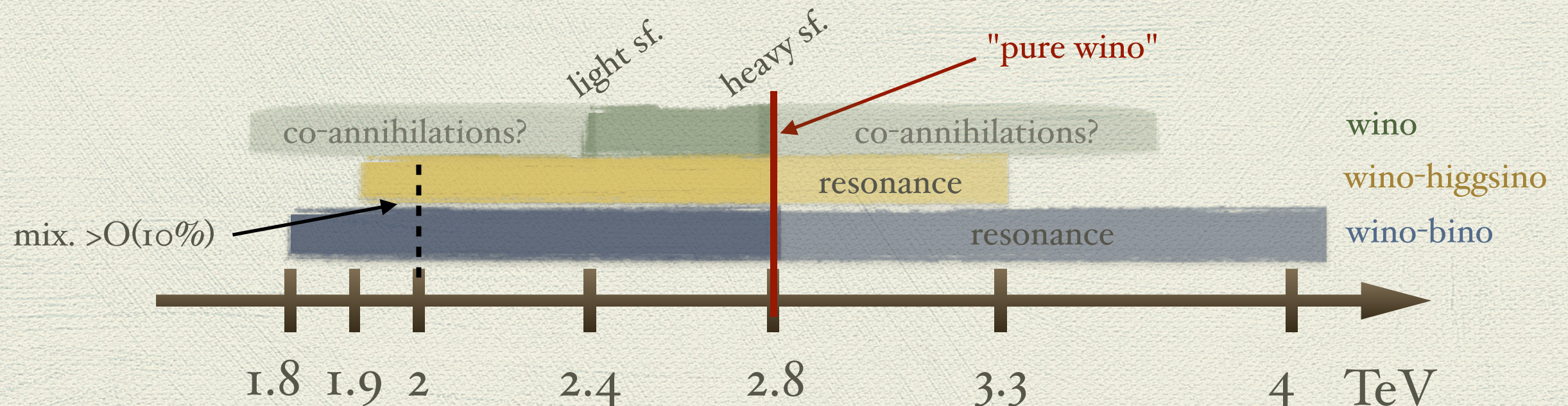
Conclusions

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



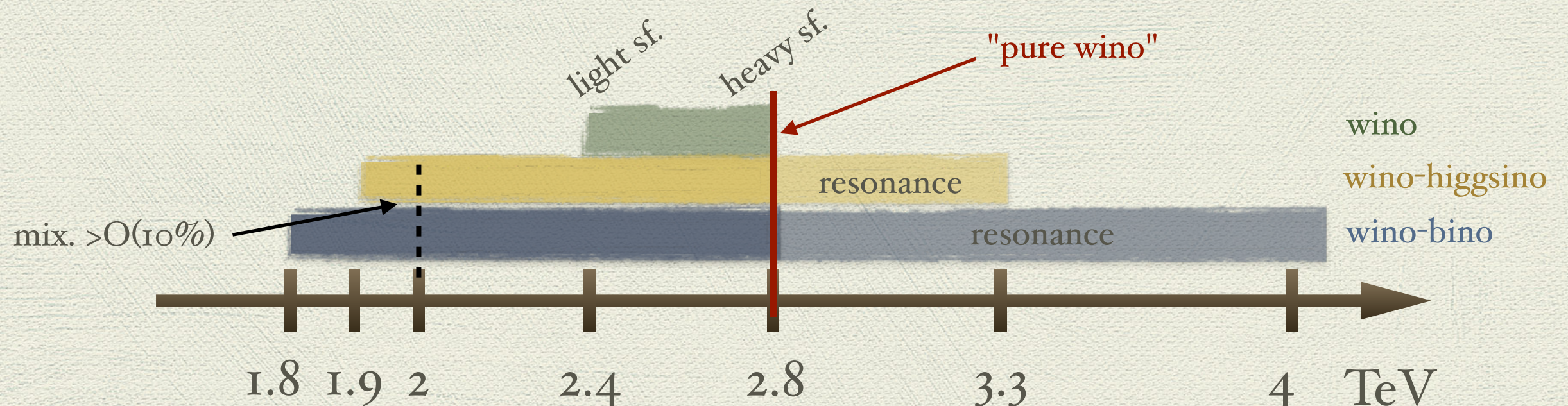
Conclusions

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



Conclusions

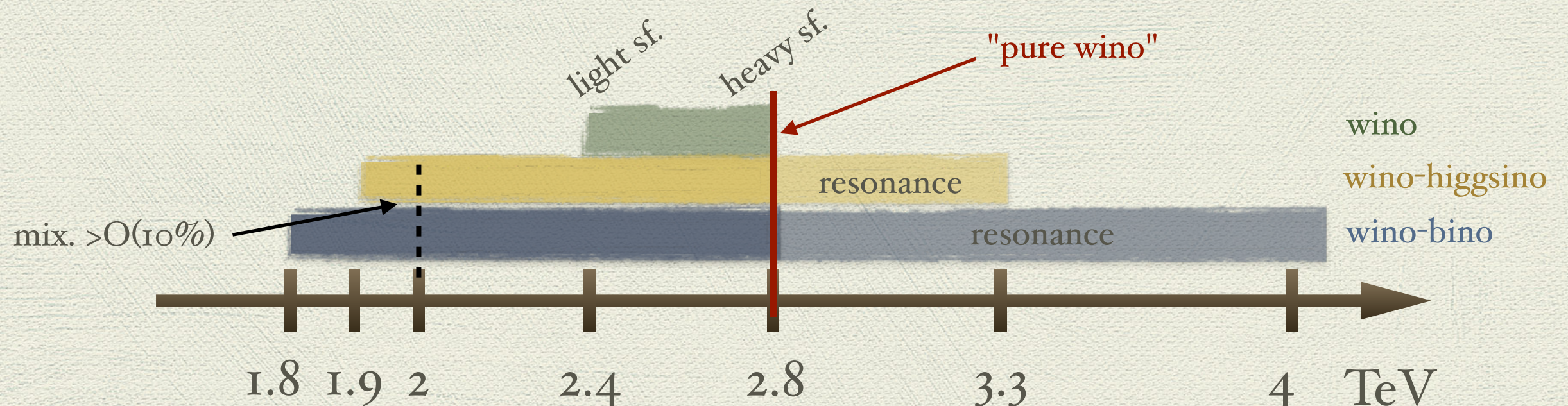
1. **Correct relic density** for wino-like neutralino in MSSM is obtained for wide range of masses:



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:

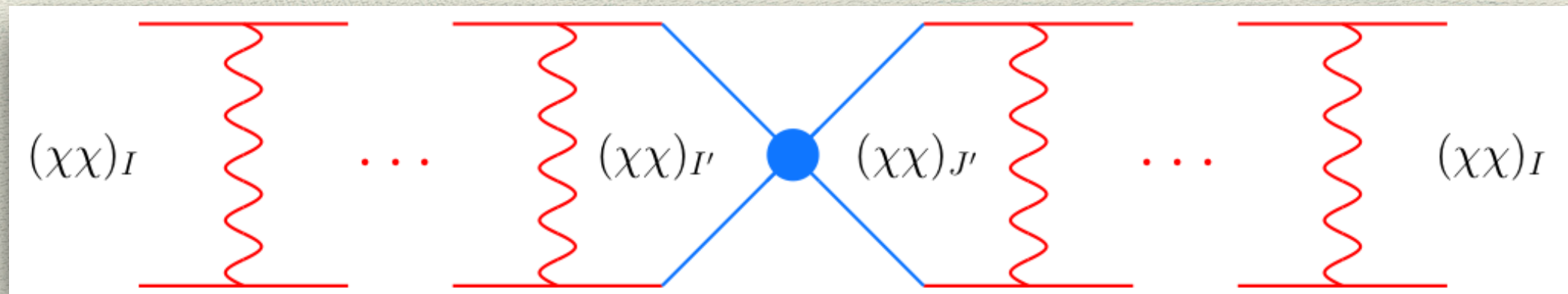


2. SE effect $> O(30\%)$ plus **resonance** \Rightarrow large ID signals
(already constrained - work in progress...)

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_χ
- 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

- 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

Only available tool for the MSSM:

DarkSE package extending the relic density by SE in **DarkSUSY**

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

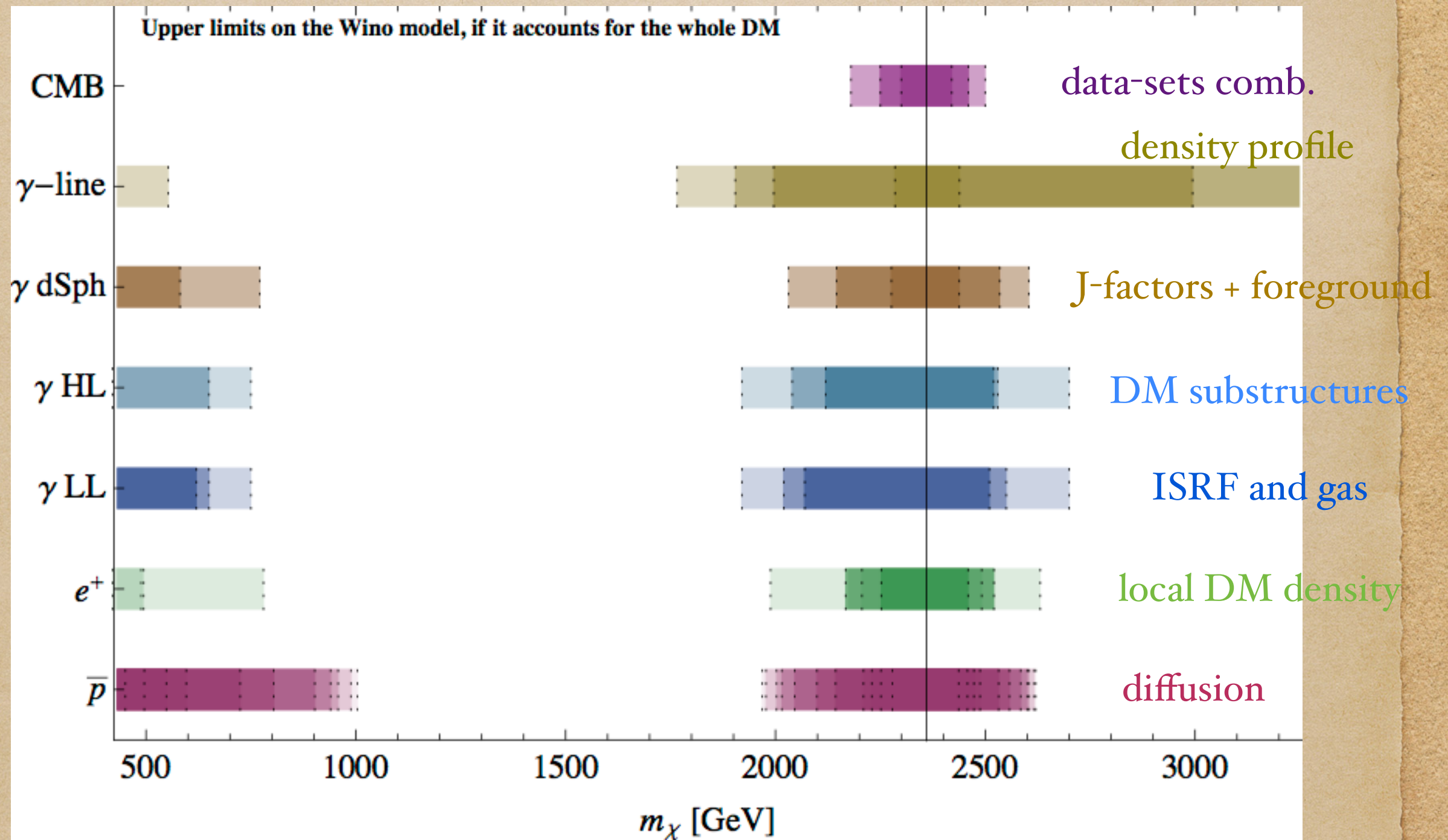
higgsino and bino fractions

common sfermion mass

Residual parameters

LIMITS ON WINO DM

UNCERTAINTIES



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