Neutralino relic density with next to leading order (co)annihilation cross section

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In collaboration with J. Harz (DESY Hamburg), B. Herrmann (LAPTH Annecy), M. Klasen (University of Münster) and K. Kovařík (KIT Karlsruhe).

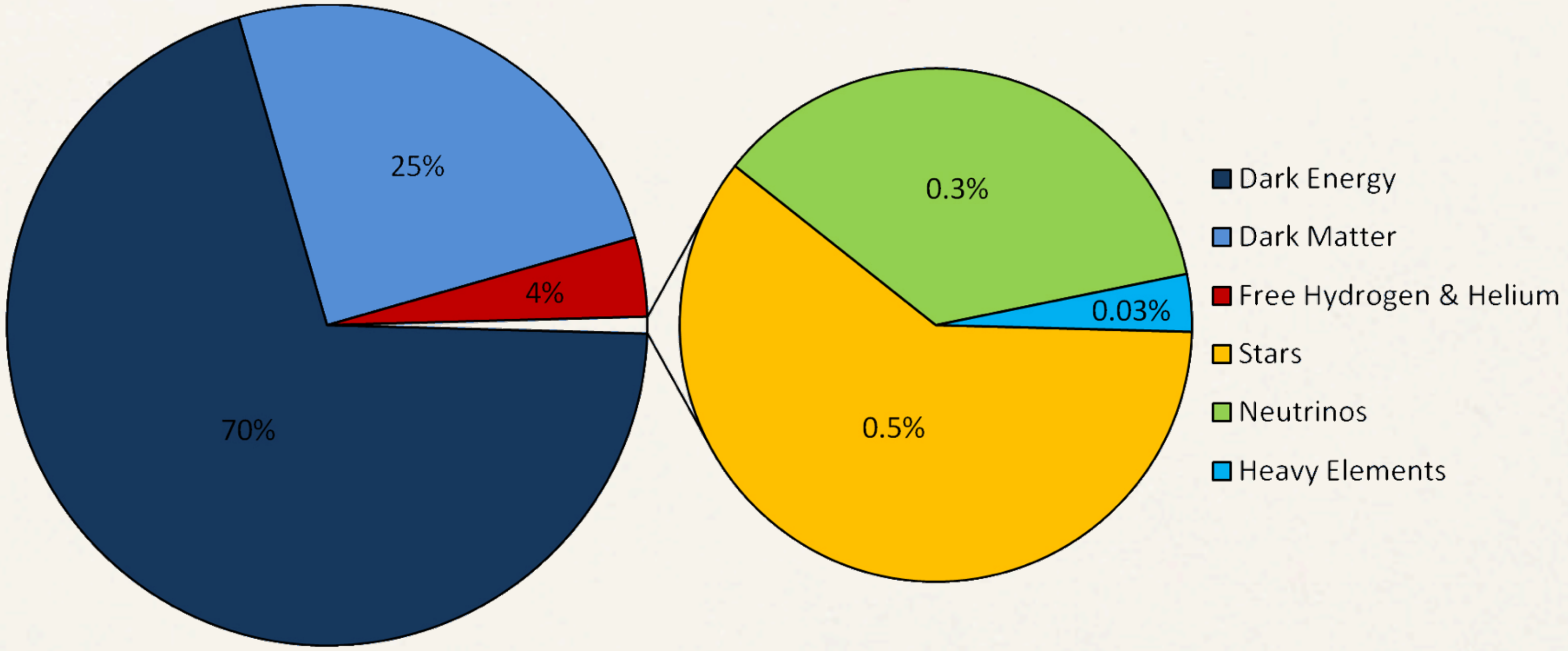
Rencontres de Physique des Particules, Montpellier - 26.04.2012

Neutralino relic density with NLO (co)annihilation cross section

- Introduction: neutralino relic density in the MSSM
- How to reduce uncertainties: the DM@NLO project
- Neutralino-squark coannihilation
- Conclusion and outlook

Introduction: neutralino relic density in the MSSM

Dark matter and our picture of the Universe



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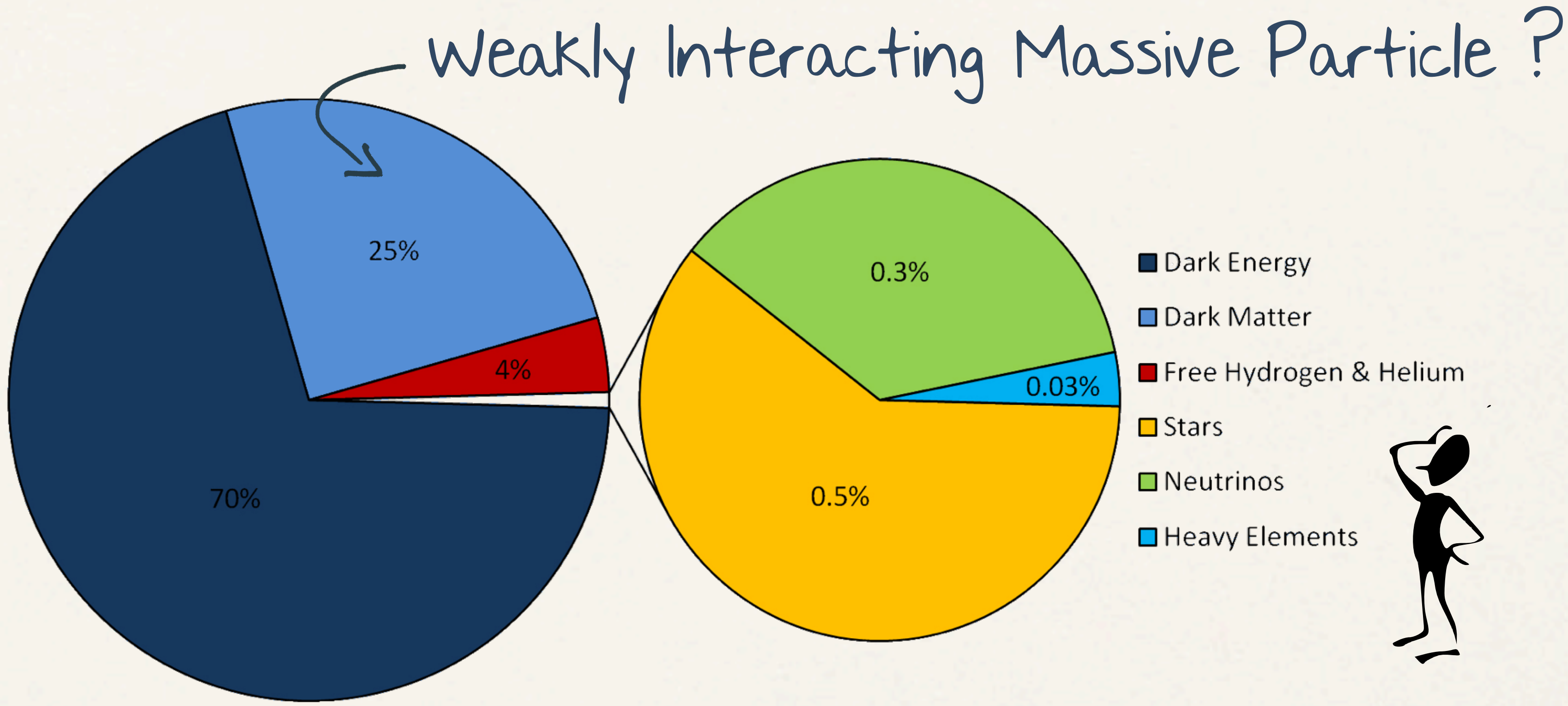

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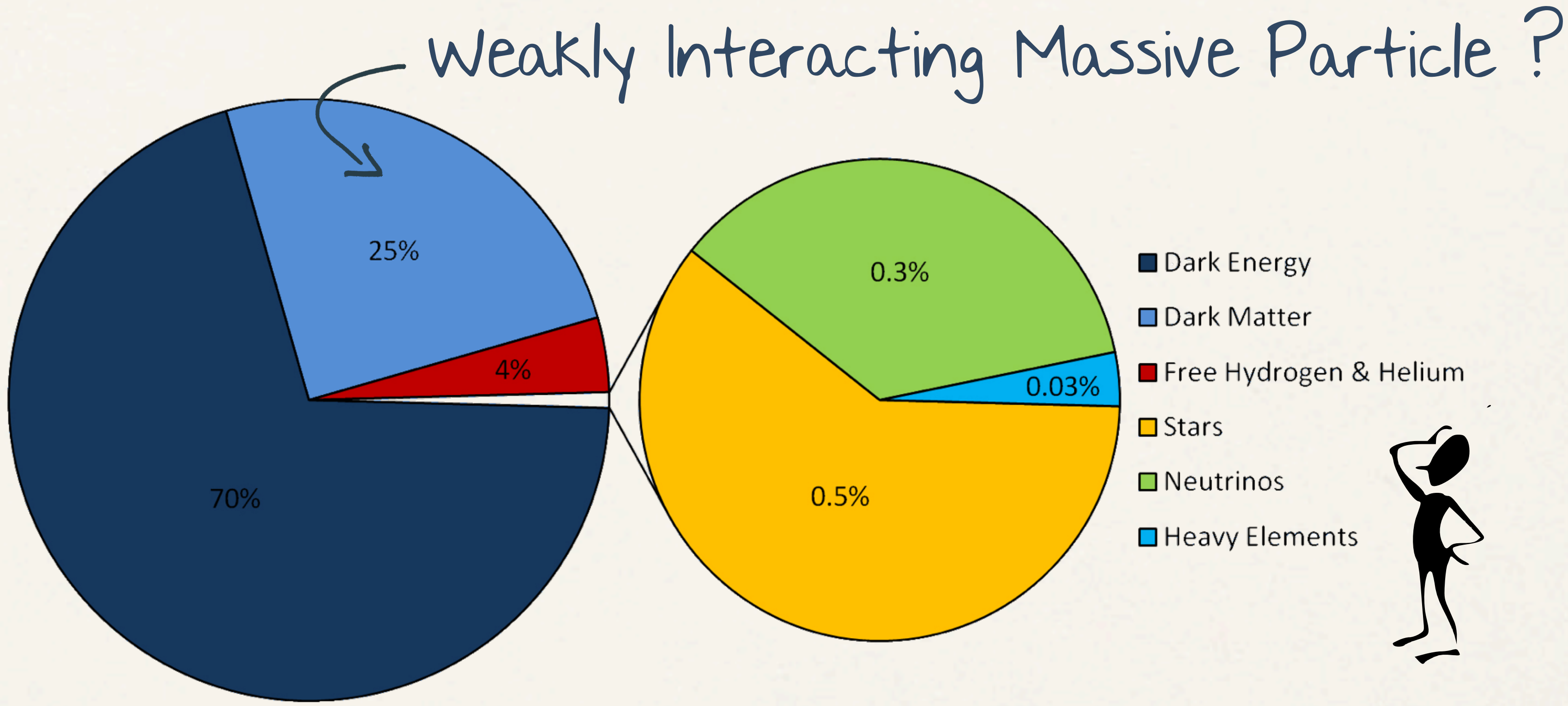
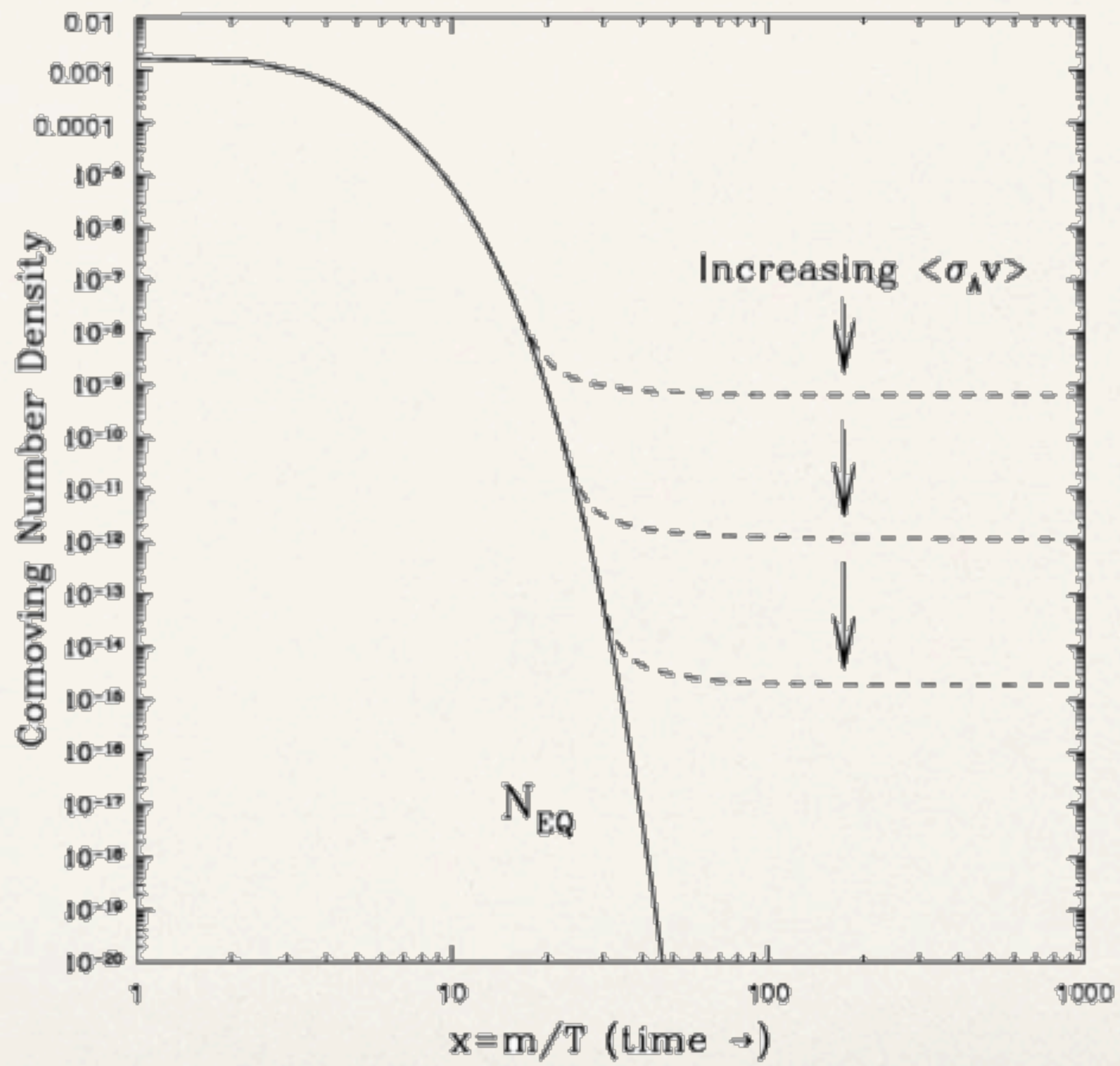


Particle physics can provide models with WIMPS, and test it experimentally:

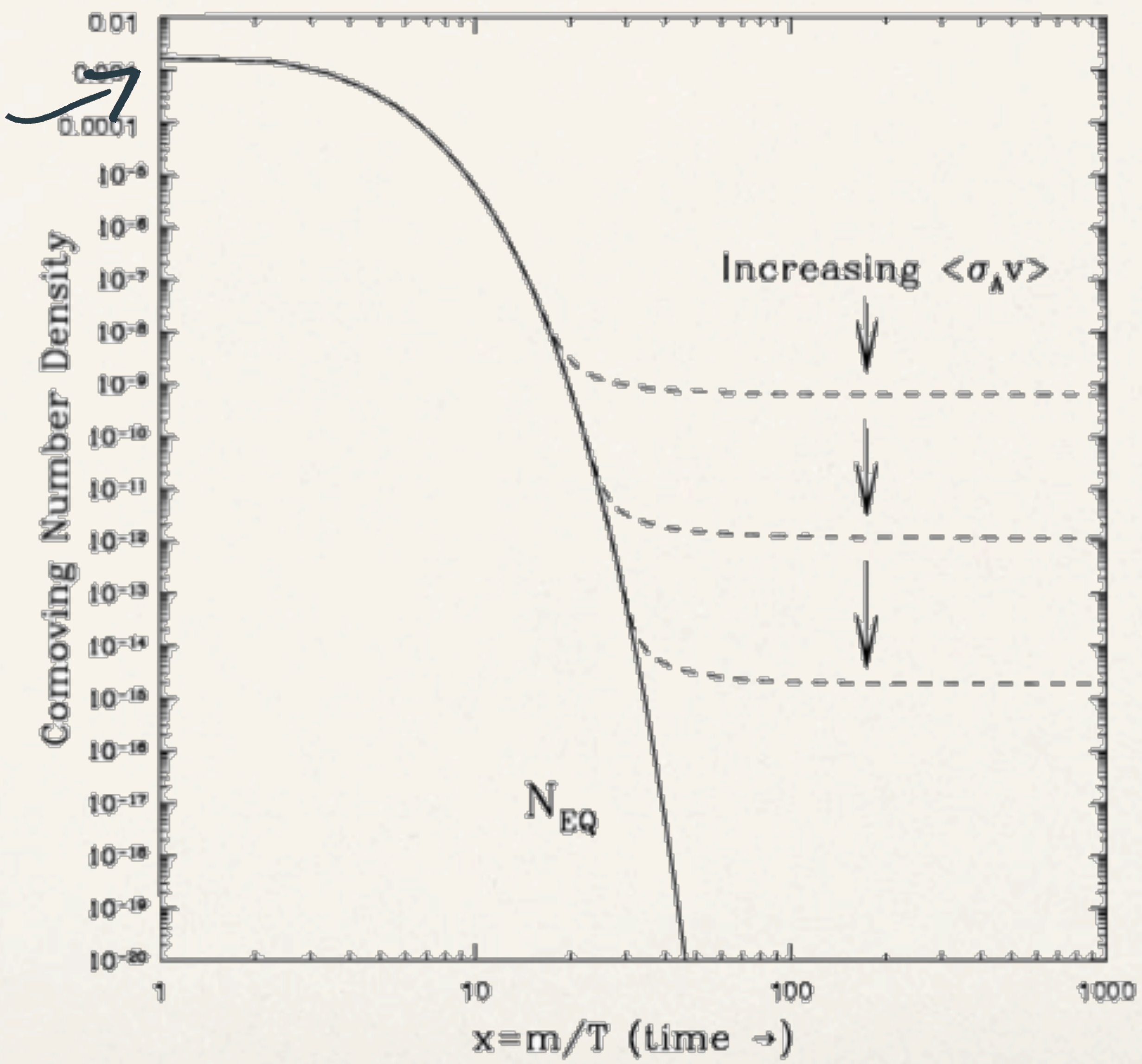
- Direct detection
- Indirect detection
- Collider production
- **Relic density** measurement

Relic density: definition



Relic density: definition

Temperature is high enough, thermal equilibrium:
XX ⇄ SM particles



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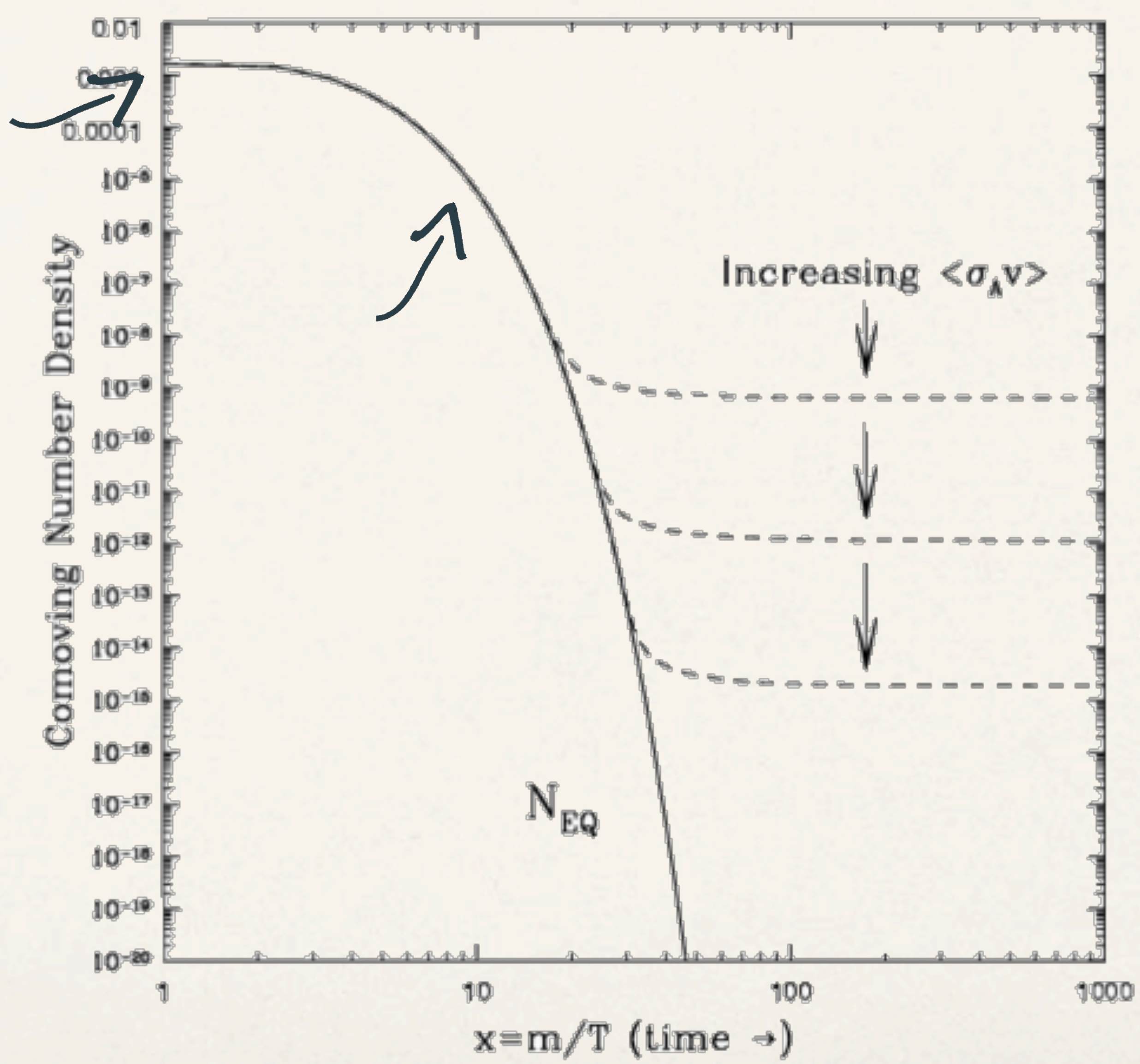
Temperature decreases, density is reduced by annihilation



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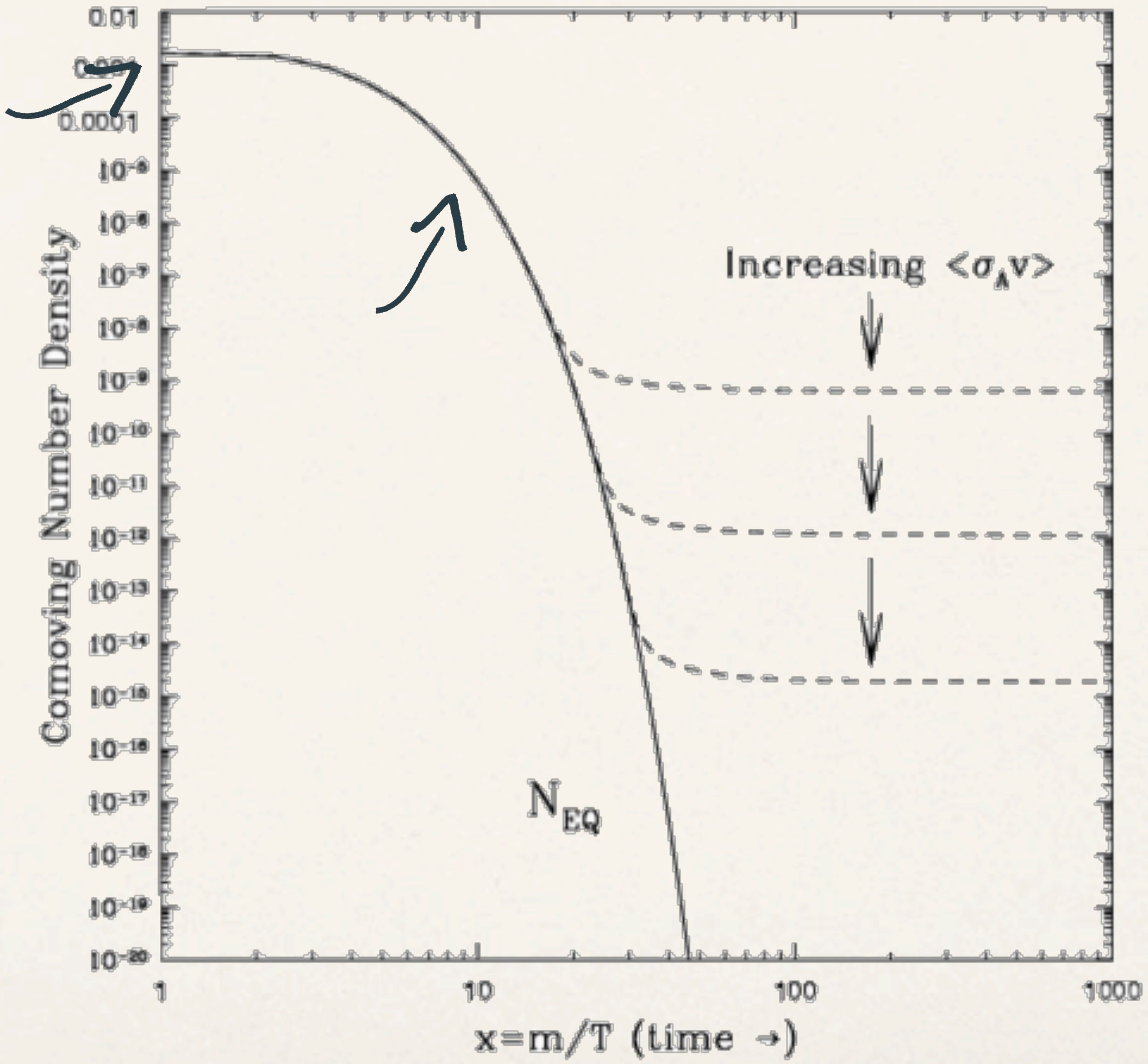

Annihilation rate lower than expansion rate: «freeze-out»

$$\Omega_c h^2 \sim \frac{1}{\langle \sigma_{\text{ann}} v \rangle}$$

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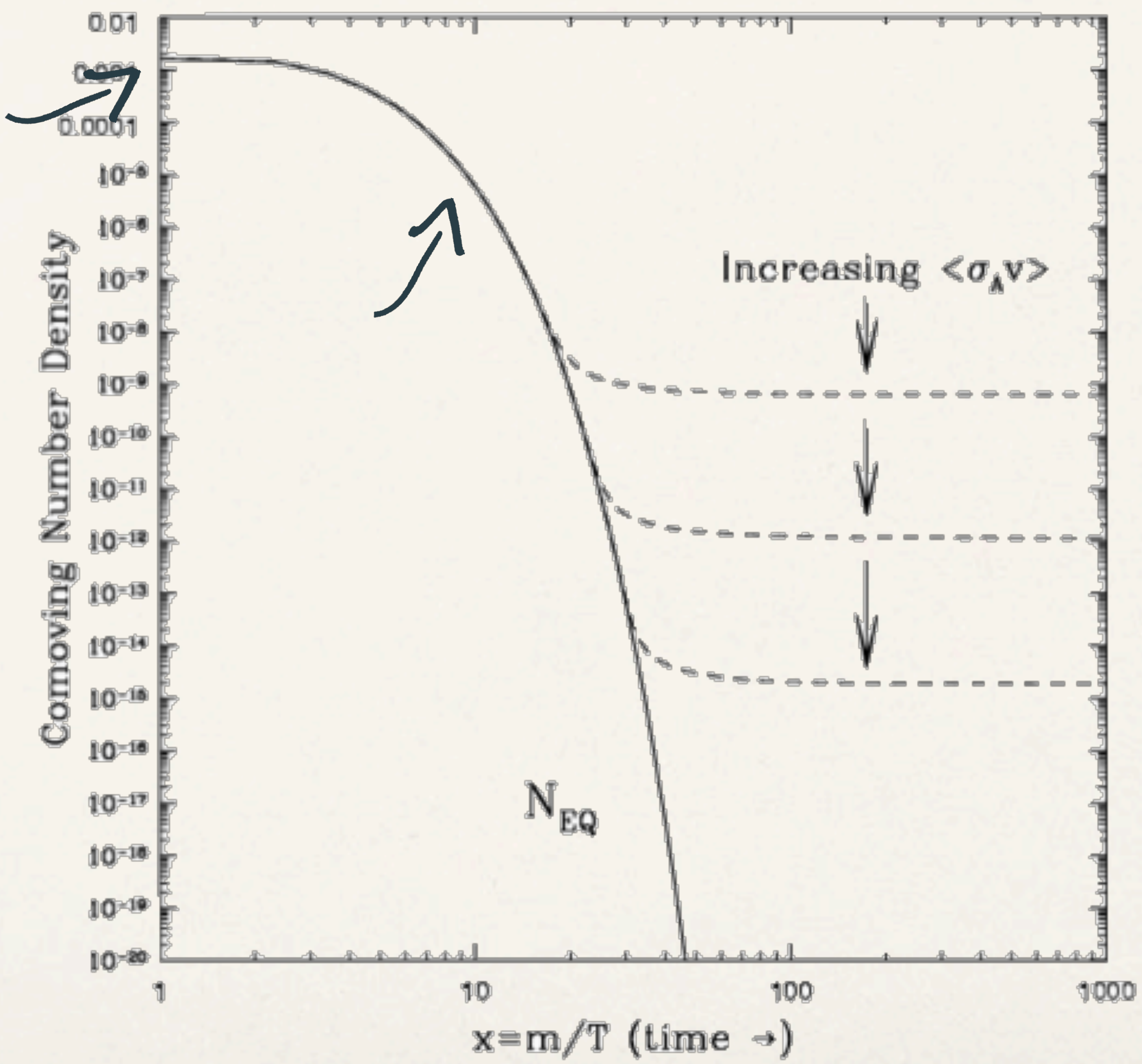

Annihilation rate lower than expansion rate: «freeze-out»

$$\Omega_c h^2 \sim \frac{1}{\langle \sigma_{\rm ann} v \rangle}$$

Relic density is measured by WMAP: $\Omega_{\rm CDM} h^2 = 0.1126 \pm 0.0036$

Relic density: calculation

Need to solve the Boltzmann equation:

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -3Hn - \langle \sigma_{\mathrm{ann}} v \rangle \left(n^2 - n_{\mathrm{eq}}^2\right)$$

↖ particle physics !

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particle physics !

Where the thermally averaged total cross-section is:

$$\langle \sigma_{\mathrm{ann}} v \rangle = \sum_{i,j=0}^{N} \langle \sigma_{ij} v_{ij} \rangle \frac{g_i g_j}{g_{\mathrm{eff}}^2} \left(\frac{m_i m_j}{m_0^2}\right)^{3/2} \exp\left\{ -\frac{(m_i + m_j - 2m_0)}{T} \right\}$$

(co)annihilation cross-sections

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(co)annihilation cross-sections

Different tools calculating dark matter relic density exists, such as **MicrOmegas,** DarkSUSY and SuperIso Relic.

The neutralino: a supersymmetric WIMP

Our DM candidate: the MSSM neutralino

Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name
$\tilde{q}_L, \tilde{q}_R$	left and right squark	$\tilde{q}_1, \tilde{q}_2$	squark 1 and 2
$\tilde{l}_L, \tilde{l}_R$	left and right slepton	$\tilde{l}_1, \tilde{l}_2$	slepton 1 and 2
$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
$\tilde{g}$	gluino	$\tilde{g}$	gluino
$\tilde{W}^{\pm}$	charged winos	$\tilde{\chi}^{\pm}_{1,2}$	charginos
$\tilde{H}^{-}_{1}$	higgsino −		
$\tilde{H}^{+}_{2}$	higgsino +		
$\tilde{B}$	bino	$\tilde{\chi}^{0}_{1,2,3,4}$	neutralinos
$\tilde{W}^{3}$	neutral wino		
$\tilde{H}^{0}_{1,2}$	neutral higgsinos		

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cMSSM parameters

m_0, $m_{1/2}$, A_0, $\tan\beta$, sign(μ)

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↓ RGE

Spectrum (masses and mixings)

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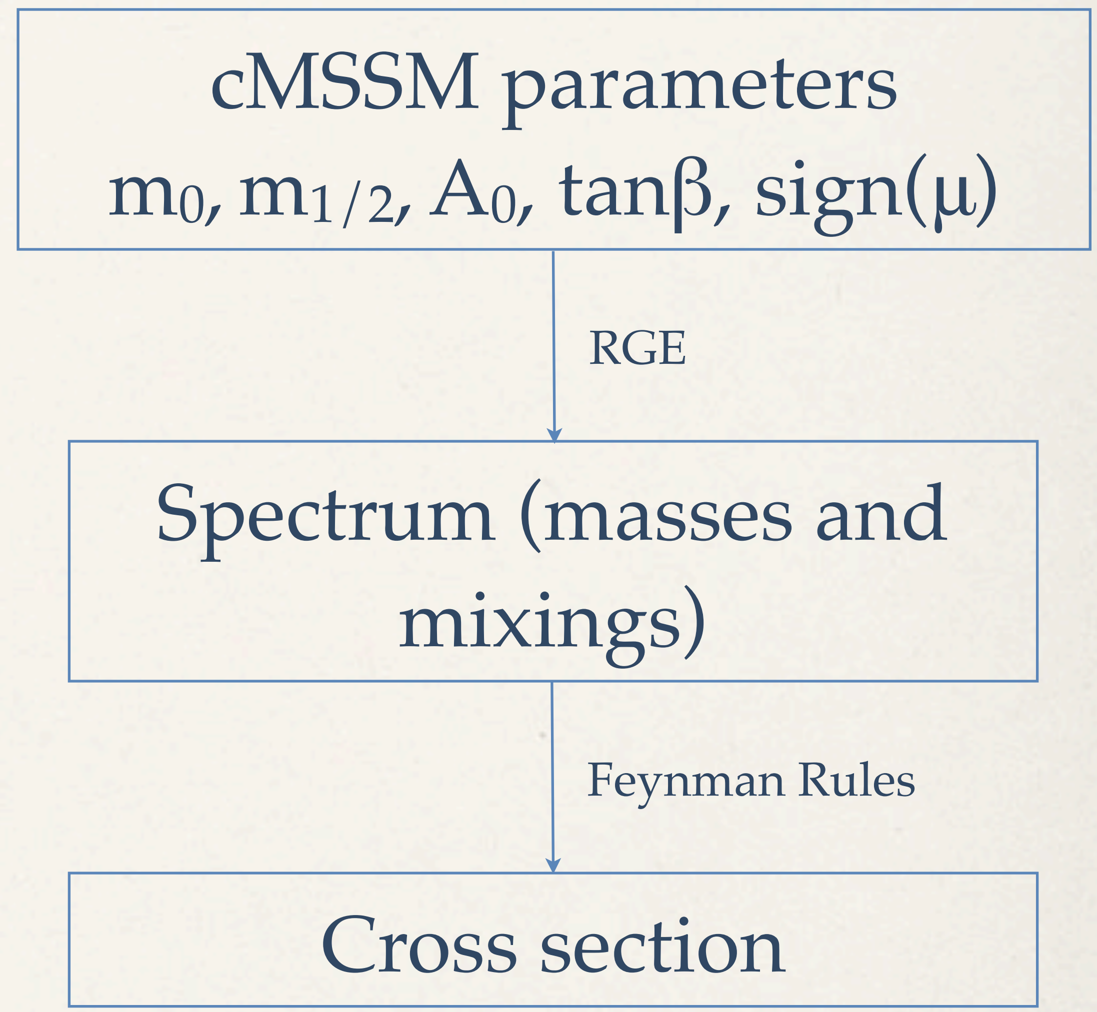

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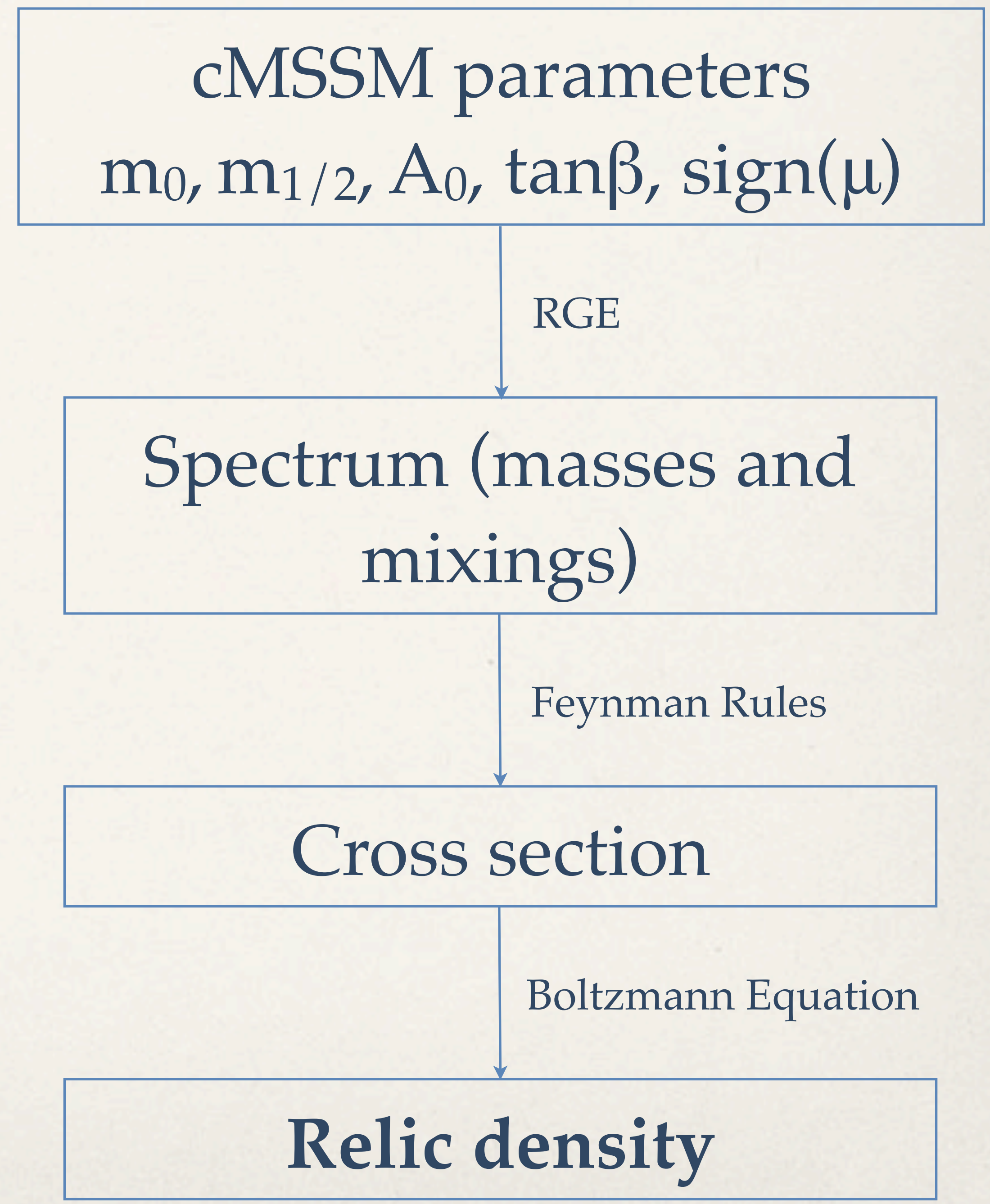
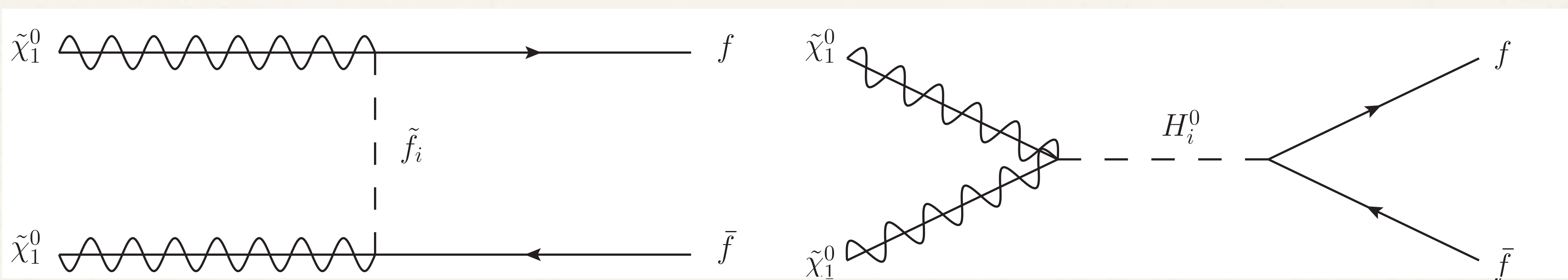


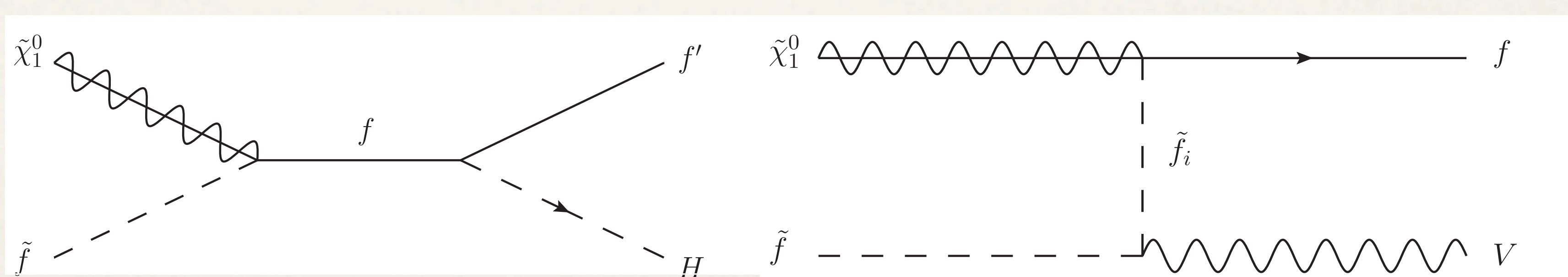
Neutralino annihilation and coannihilation processes

- Different annihilation processes contributes to the cross-section. For example annihilation into fermions:



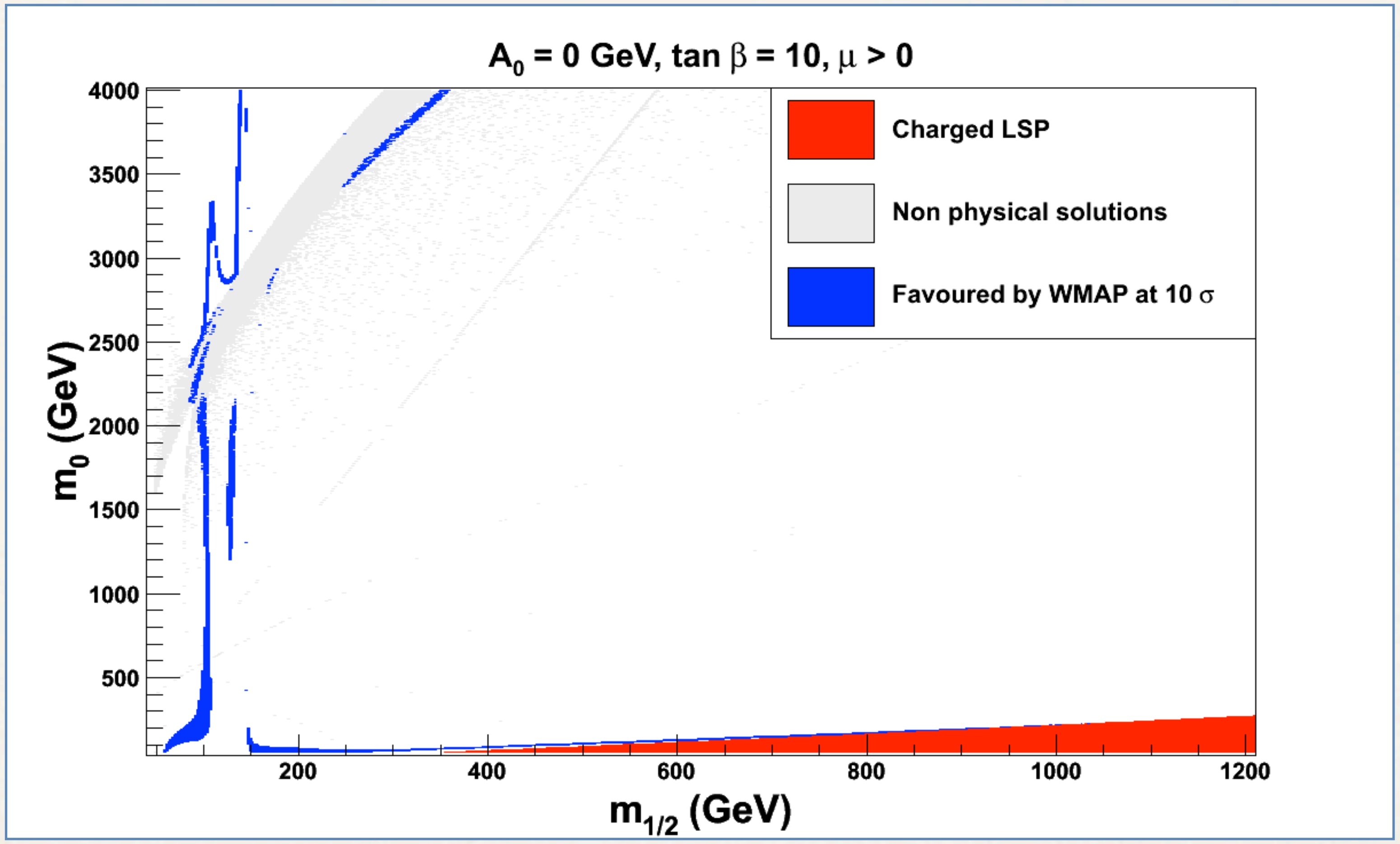
- But coannihilation with a sfermion also contributes when $m_{\tilde{\chi}_1^0} \approx m_{\tilde{f}}$:

(Possible with stau or stop in cMSSM)



Relic density in the cMSSM

Depending on the spectrum, contributions to the total cross-section will be different, leading to different allowed regions:



Relic density is a very stringent constraint ⟶ need for a high precision calculation

How to reduce uncertainties: the DM@NLO project

Experimental uncertainties

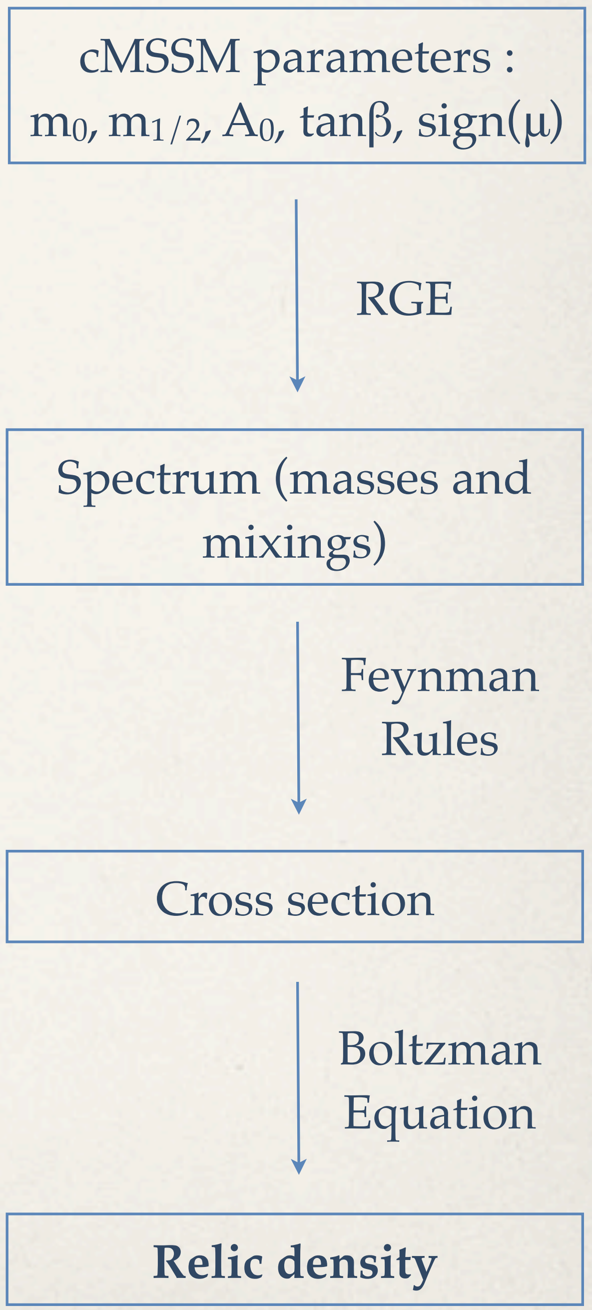
Current value: $\Omega_{\mathrm{CDM}}h^2 = 0.1126 \pm 0.0036$

- Combination from different measurements : WMAP (CMB anisotropies), type Ia Supernovae, and Baryon Acoustic Oscillations.
- Uncertainty of 3%.
- Planck will do one order of magnitude better !
- To benefit from this, we need to reduce uncertainty of theoretical prediction.

Theoretical uncertainties

Sources of theoretical uncertainty:

- Precision of Renormalization Group Equations
- Standard model parameters (esp. top mass)
- 3 body final states
- **Precision of cross section calculation**
- QCD equation of state (effective d.o.f)
- Cosmological model



Precision of cross section calculation

- Most of the public codes calculate cross section at tree-level
- MicrOmegas also include some effective corrections
- However the full one loop corrections are not included, and known to be important:
  - Electroweak corrections studied by «SLOOPS» collaboration

    N. Baro, F. Boudjema, A. Semenov [Phys. Rev. D 78 (2008)]
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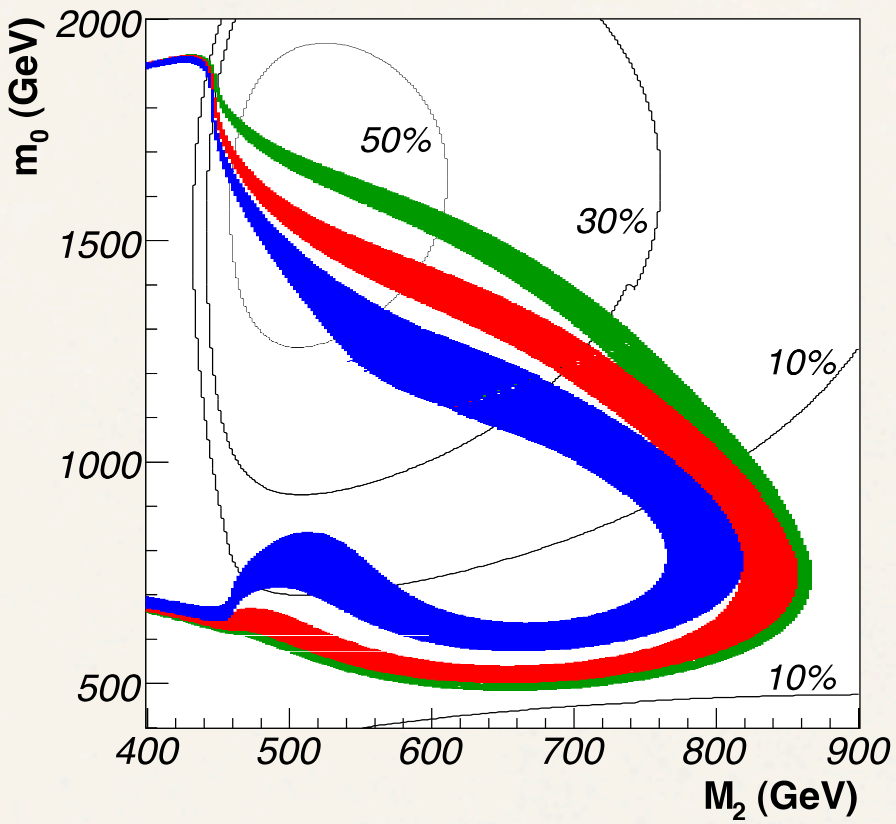
only QCD here !

A numerical example: neutralino annihilation into quarks

B. Herrman, M. Klasen, K. Kovařík
[Phys. Rev. D 80, 085025 (2009)]



Tree-level
Effective one-loop (MicrOmegas)
Full one-loop

- The authors calculated one loop QCD corrections to the neutralino annihilation into quarks cross section
- They used MicrOmegas to deduce the relic density
- Impact of corrections larger than experimental uncertainty
- The favoured region in the parameter space is shifted by ~100 GeV compared to the tree-level calculation

The DM@NLO project

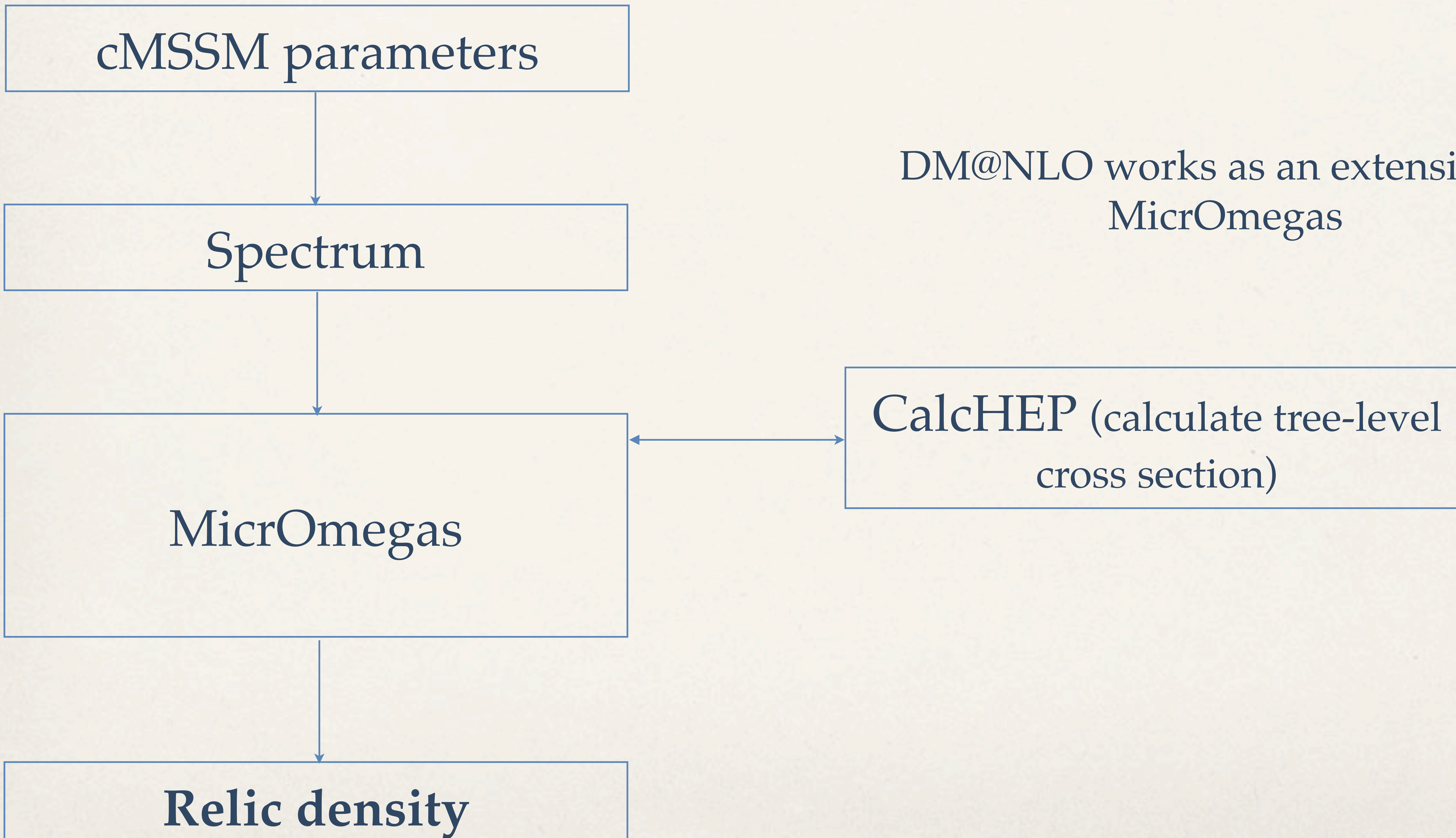
Conclusion: QCD loop corrections have to be taken into account!

→ DM@NLO («Dark Matter At Next to Leading Order») project:

- Provide an **automatic** code to calculate the neutralino annihilation and coannihilation cross sections with the **full** one loop SUSY-QCD corrections.
- Can be linked to MicrOmegas to calculate relic density with a better precision.

http://dmnlo.hepforge.org/

The DM@NLO project



DM@NLO works as an extension of MicrOmegas

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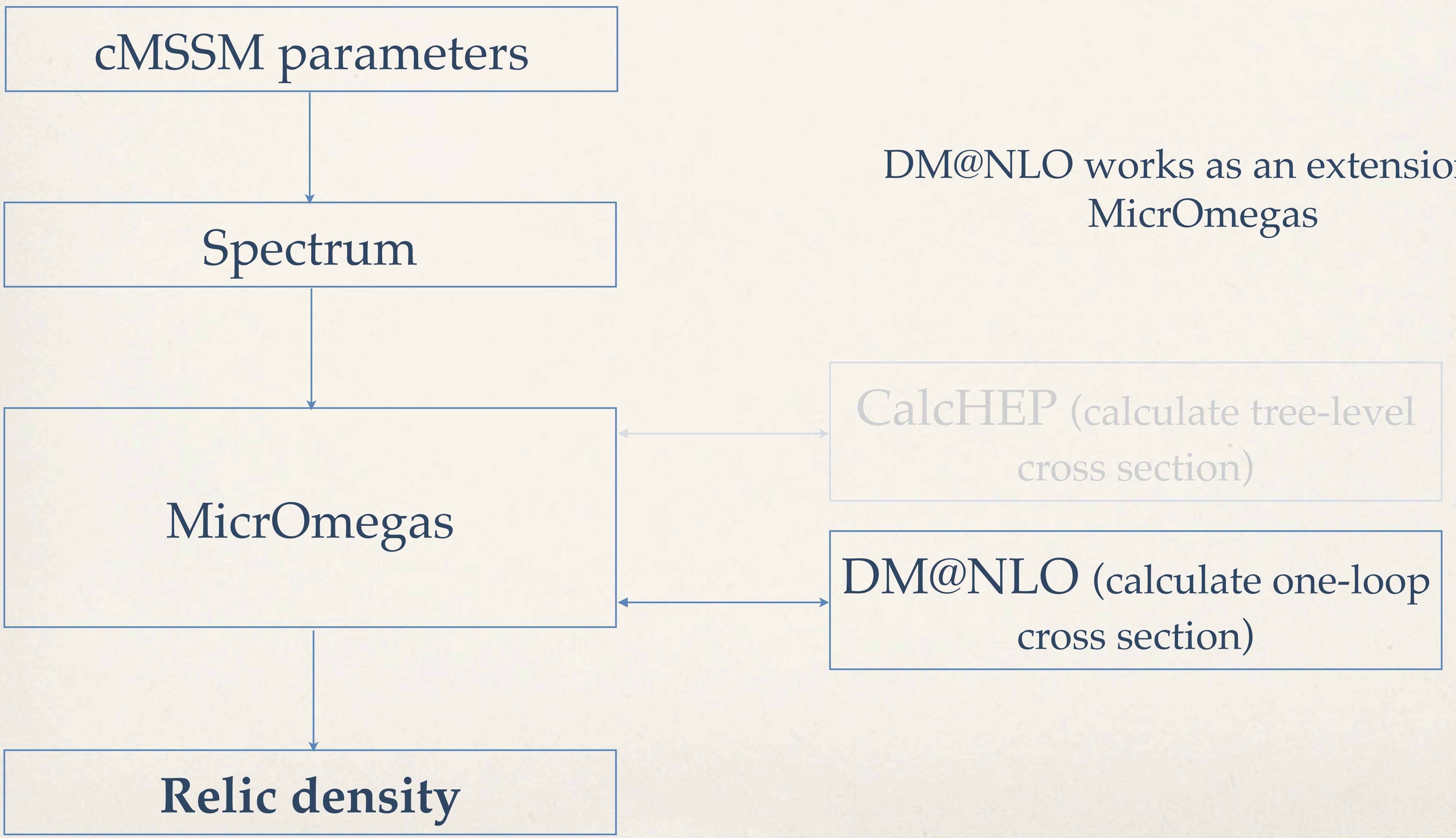

The DM@NLO project

Which Feynman diagrams are relevant for QCD corrections ? The ones which contains quarks and/or squarks:

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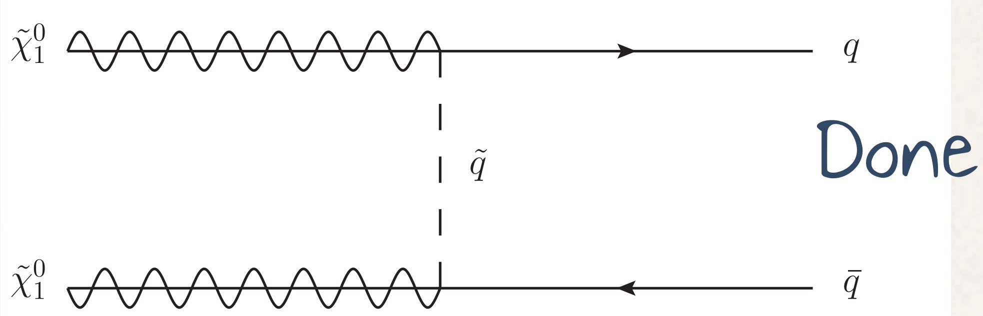
- Annihilation of neutralino into quarks



Done !

The DM@NLO project

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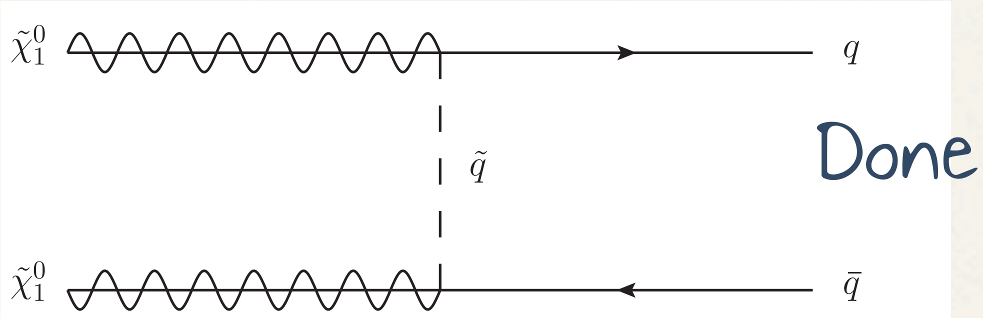
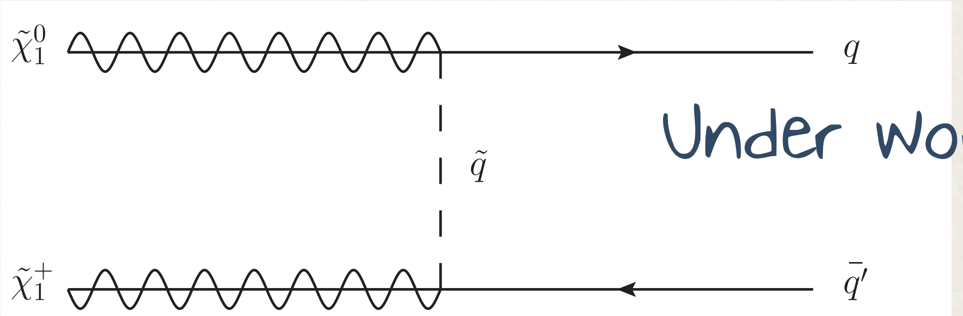


Done !

- Coannihilation neutralino / chargino into quarks

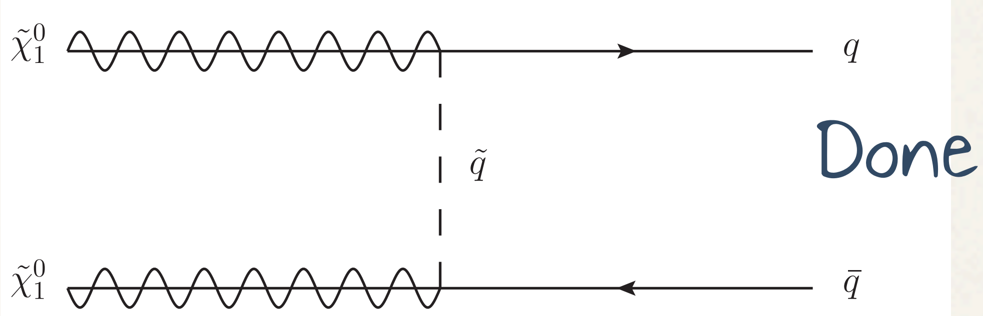


Under work

The DM@NLO project

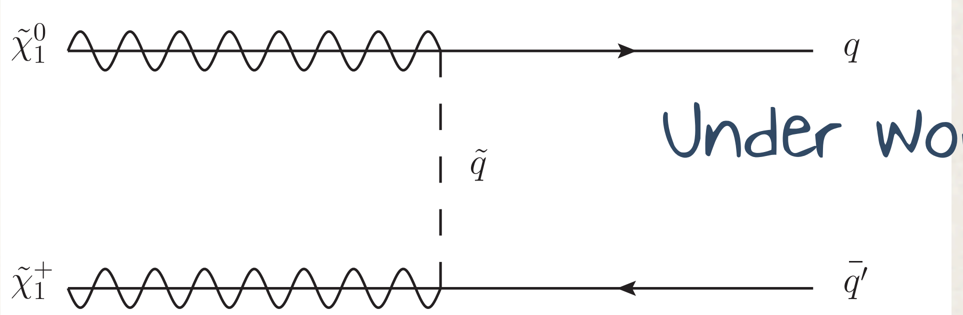
Which Feynman diagrams are relevant for QCD corrections ? The ones which contains quarks and/or squarks:

- Annihilation of neutralino into quarks



Done !

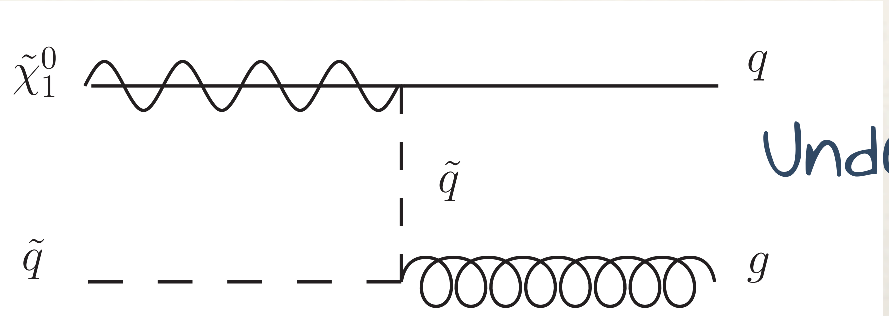
- Coannihilation neutralino/chargino into quarks



Under work

- **Coannihilation neutralino squark** into quark and vector/higgs boson

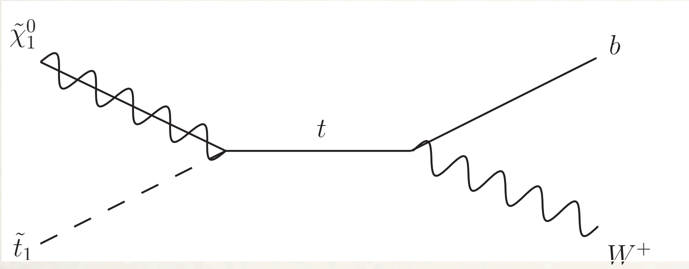
See next part of the talk !

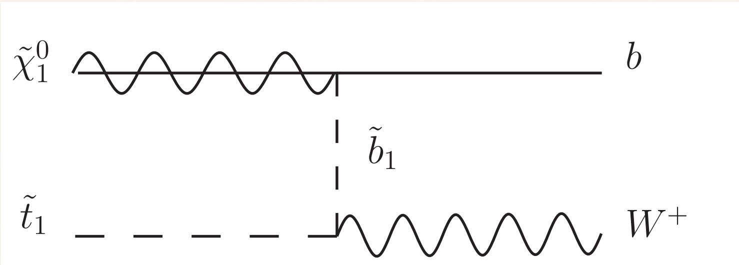


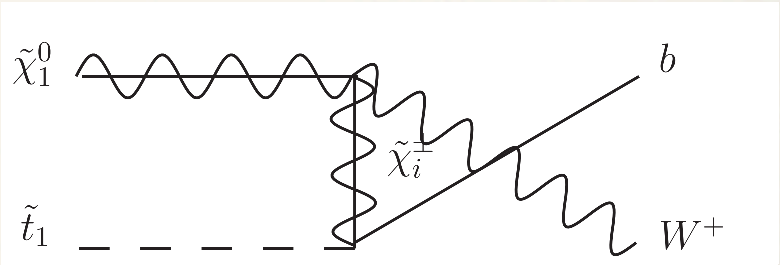
Under work

Neutralino-squark coannihilation

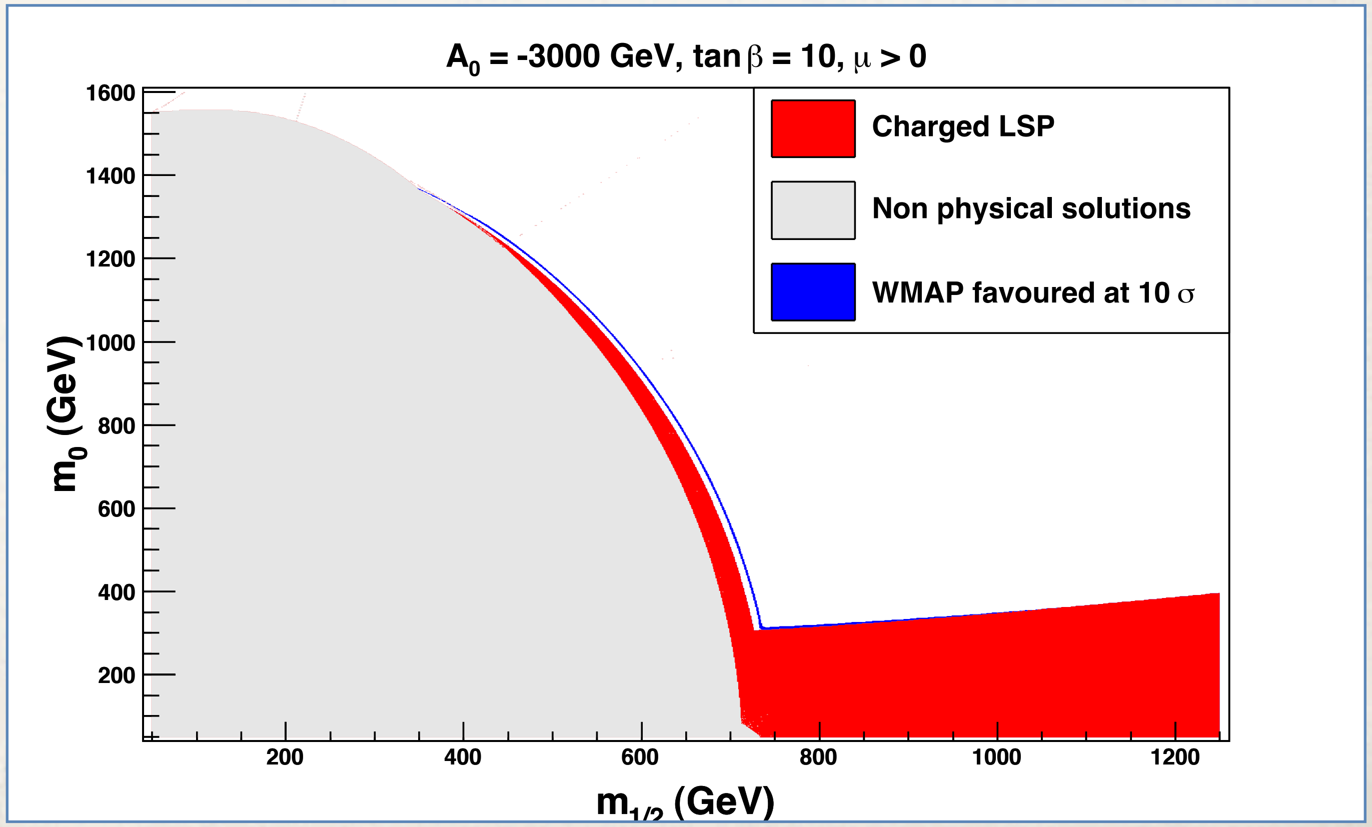
Phenomenology of neutralino-stop coannihilation







- Important contribution when $m_{\tilde{\chi}_1^0} \approx m_{\tilde{f}}$, i.e. stop has to be light
- Easy to achieve because splitting proportional to Yukawa
- Possible in the cMSSM for large A_0:
- Good for baryogenesis
- Interesting collider phenomenology



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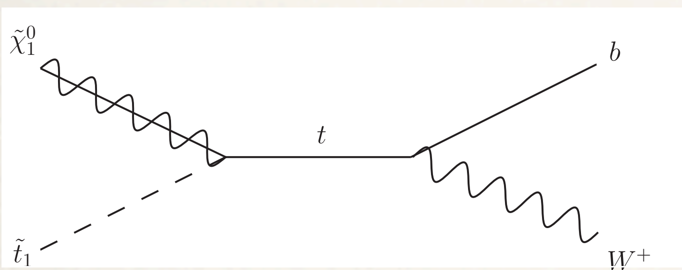
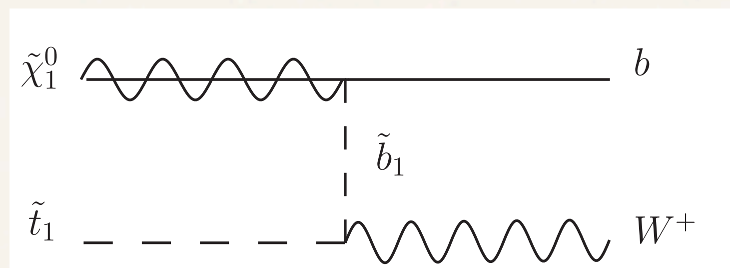
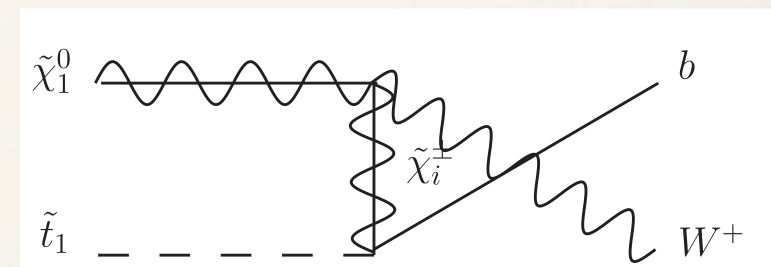


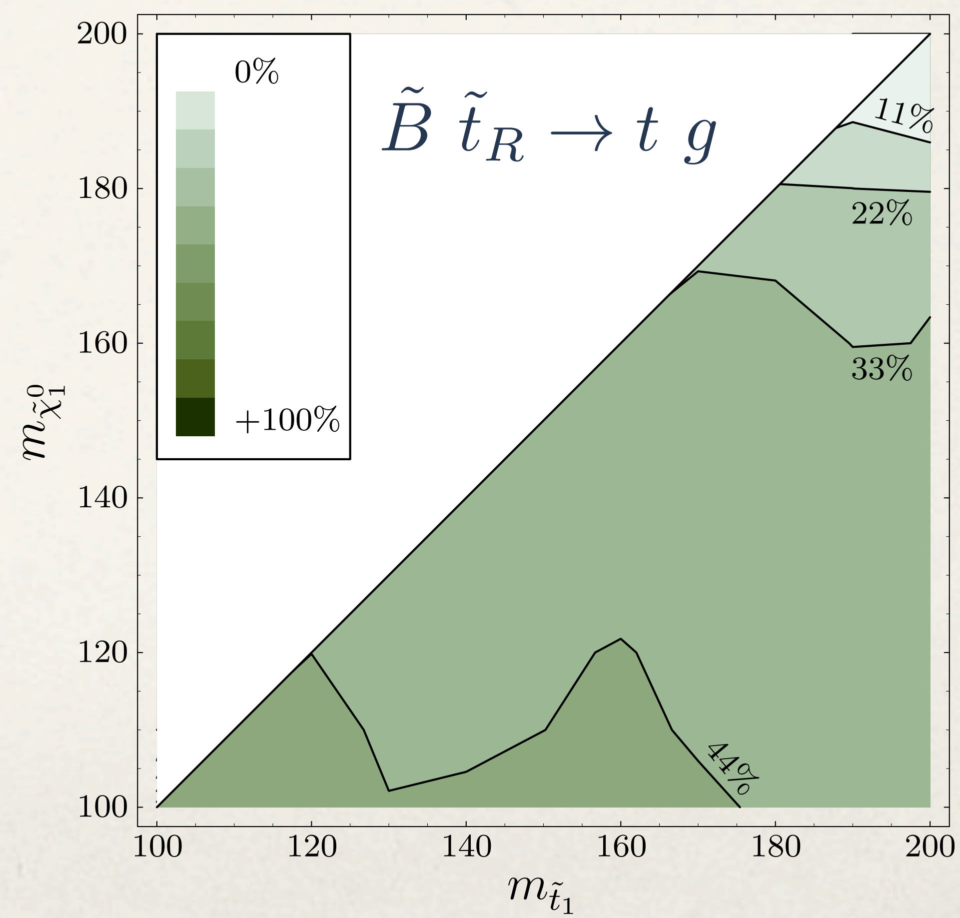




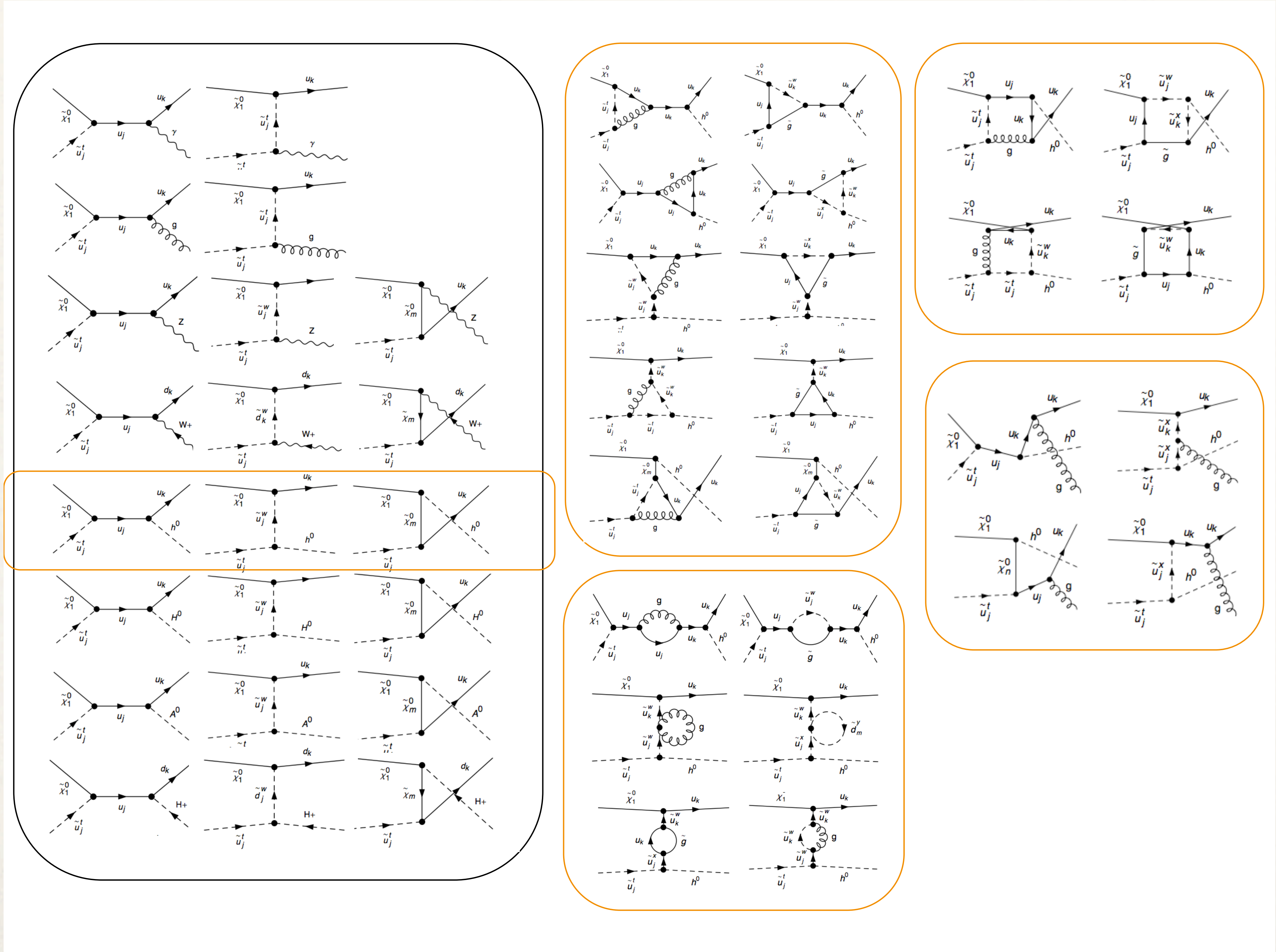
- Initial particle has color $\rightarrow$ QCD corrections expected to be large
- Was confirmed by first approximations:

  A. Freitas [Phys. Let. B 652 (2007)]

- We want to calculate the complete corrections
- First step: identify all contributing diagrams!

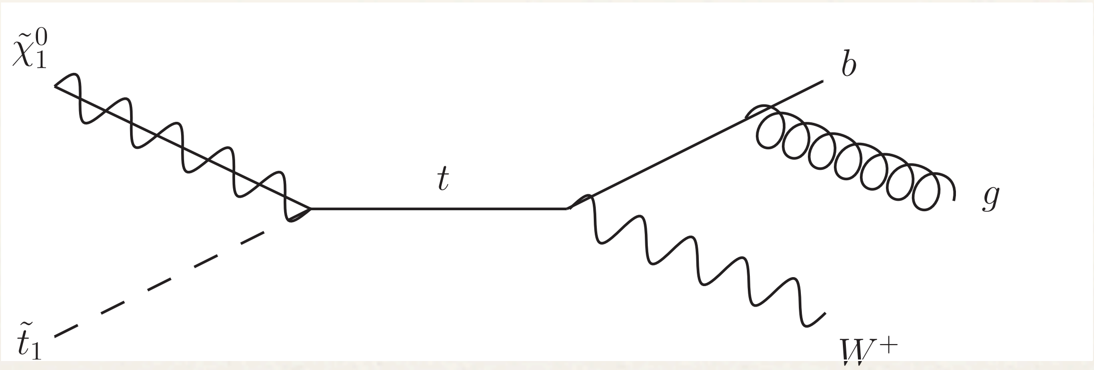


Tree-level and NLO diagrams



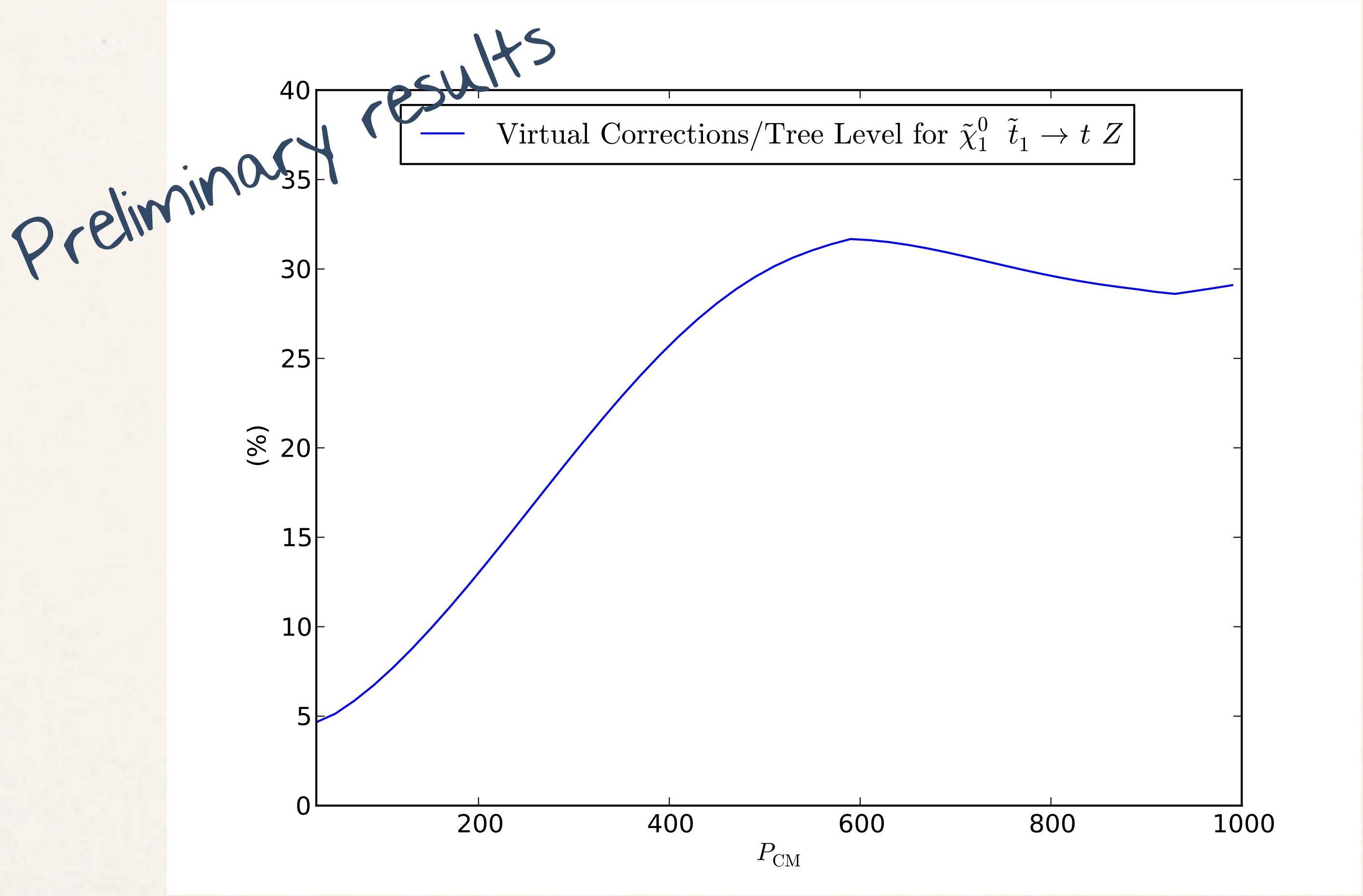
Some challenges

- Implementing thousands of amplitudes requires a general and efficient algorithm
- Renormalization scheme to be defined carefully
- Dipole substraction method to be generalized for massive colored initial state



Status of the project

- Non abelian virtual corrections implemented and (almost) checked



- Real emission processes under work

- Full one loop coannihilation will be ready in a few months !

Conclusion and outlook

Conclusion :

- Constraints on SUSY models from dark matter relic density is more and more stringent.
- Theoretical calculations need to be more and more precise
- One possibility is to calculate cross-sections at higher order. The DM@NLO project aims at dealing with the QCD corrections.
- Neutralino annihilation is implemented, coannihilation under work.

Outlook :

- Finish implementation and perform physical analysis
- Add corrections to squark annihilation ?
- Calculate corrections to (in)direct detection ?
- Extend to other models ?