Status of micromegas

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Plan

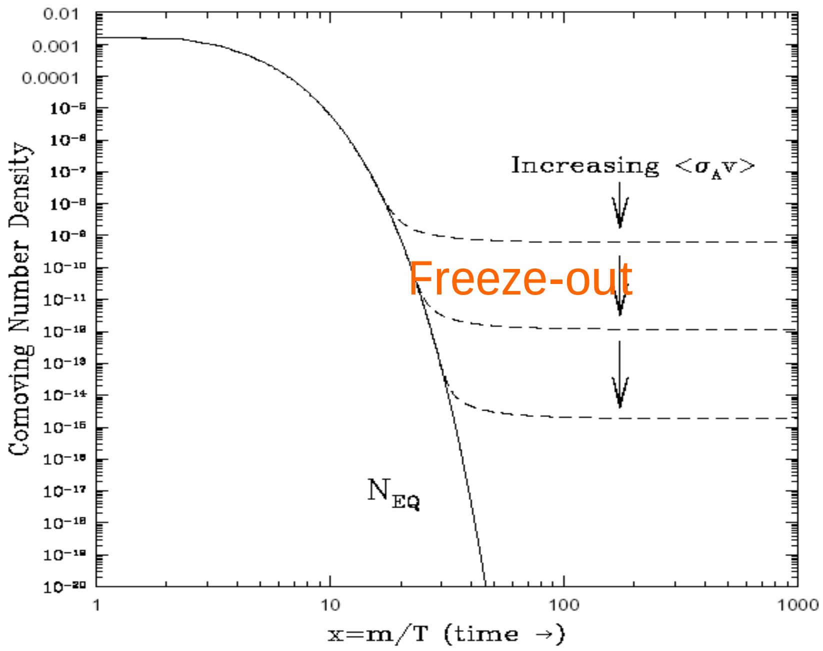
- Motivation and general presentation
- Description of micromegas_1.3.6
- micromegas_nmssm
- New developments
- Outlook and conclusion

Motivation

- Strong evidence for dark matter
- CMB (WMAP) gives precise information on the amount of dark matter
- Most attractive explanation for dark matter: new weakly interacting particle, for example those present in R-parity conserving SUSY model
- WMAP measurement strongly constrains models of cold dark matter in particular supersymmetric models
- Need for a precise and accurate computation of the relic density of dark matter
- Codes that compute relic density +… :
  - Neutdriver, DarkSUSY, micrOMEGAs, Isatools
  - Many private codes: SSARD (Olive), Drees, Roskowski …

Relic density of wimps

- In early universe WIMPs are present in large number and they are in thermal equilibrium
- As the universe expanded and cooled their density is reduced through pair annihilation
- Eventually density is too low for annihilation process to keep up with expansion rate
  - Freeze-out temperature
- LSP decouples from standard model particles, density depends only on expansion rate of the universe



$$\frac{dn}{dt} = -3Hn - <\sigma v> \left[n^2 - n_{eq}^2\right]$$

- Relic density

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} \; .$$

- A relic density in agreement with present measurements $\Omega h^2 \sim 0.1$ requires typical weak interactions cross-section

Coannihilation

- If M(NLSP)~M(LSP) then $\chi + X \longrightarrow \chi' + Y$ maintains thermal equilibrium between NLSP-LSP even after SUSY particles decouple from standard ones

- Relic density depends on rate for all processes involving LSP/NLSP → SM
- All particles eventually decay into LSP, calculation of relic density requires summing over all possible processes

Exp(- ΔM)/T

$$< \sigma v >= \frac{\sum_{i,j} g_i g_j \int_{(m_i+m_j)^2} ds \sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sigma_{ij}(s)}{2T\left(\sum_i g_i m_i^2 K_2(m_i/T)\right)^2}$$

- Important processes are those involving particles close in mass to LSP

micromegas

- C code
- Complete tree-level matrix elements for all subprocesses
- Include all possible annihilation and coannihilation channels
- Calculates the relic density for any LSP
- Based on CalcHEP
- Uses the CompHEP/CalcHEP-SUSY model file obtained with LANHEP (A. Semenov)
- Solution of evolution equation and calculation of relic density with non-relativistic thermal averaging and proper treatment of poles and thresholds (Gondolo, Gelmini, NPB 360 (1991)145)
- Automatically check for presence of resonances and improves the accuracy near pole
- Includes and compiles relevant channels only if needed
- Loop-corrected Higgs masses and widths (via spectrum calculator)
- QCD corrections to Higgs couplings to fermion pairs and Δm_b corrections at large tanβ (use effective Lagrangian)

Higgs sector

- General CP conserving effective potential

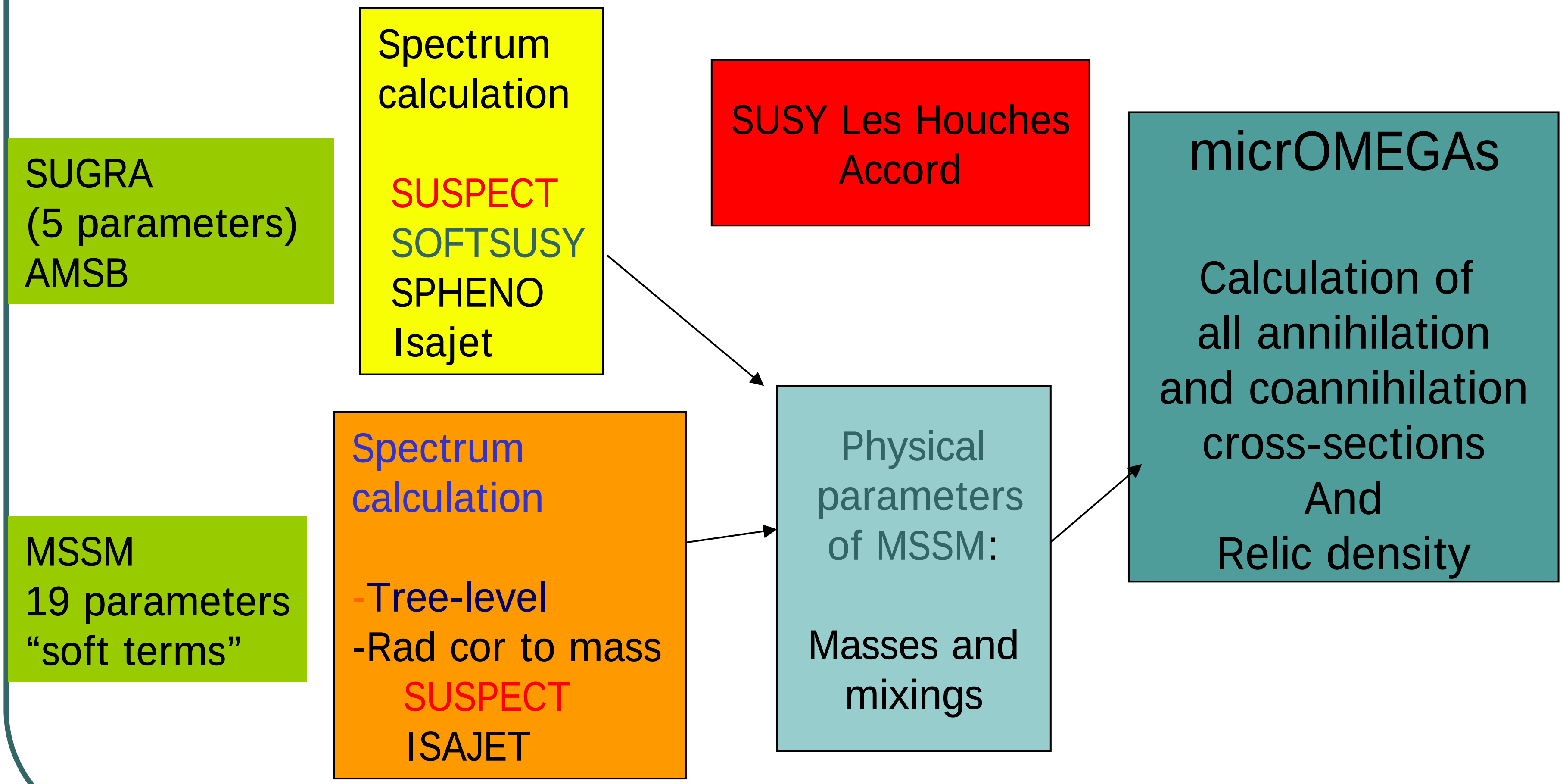
$$
\begin{aligned}
V_{eff} \;=\; & (m_1^2+\mu^2)|H_1|^2 + (m_2^2+\mu^2)|H_2|^2 - [m_{12}^2(\epsilon H_1 H_2) + h.c.] \\
& + \frac{1}{2}[\frac{1}{4}(g^2+g'^2)+\lambda_1](|H_1|^2)^2 + \frac{1}{2}[\frac{1}{4}(g^2+g'^2)+\lambda_2](|H_2|^2)^2 \\
& + [\frac{1}{4}(g^2-g'^2)+\lambda_3]|H_1|^2|H_2|^2 + [-\frac{1}{2}g^2+\lambda_4](\epsilon H_1 H_2)(\epsilon H_1^* H_2^*) \\
& + (\frac{\lambda_5}{2}(\epsilon H_1 H_2)^2 + [\lambda_6|H_1|^2+\lambda_7|H_2|^2](\epsilon H_1 H_2) + h.c.)
\end{aligned}
$$

- λ's include higher order corrections, extracted from Higgs masses and mixings (Boudjema, Semenov, hep-ph/0201219)
- SUSY-QCD correction to Higgs->bb, effective Lagrangian, relevant at large tanβ (Guasch, Hapfliger, Spira, hep-ph/0305101)

$$
\begin{aligned}
\mathcal{L}_{eff} = \sqrt{4\pi\alpha_{QED}}\frac{m_b}{1+\Delta m_b}\frac{1}{2M_W\sin\theta_W}\Bigg[& -Hb\bar{b}\frac{\cos\alpha}{\cos\beta}\left(1+\frac{\Delta m_b\tan\alpha}{\tan\beta}\right) \\
& + iAb\bar{b}\tan\beta\left(1-\frac{\Delta m_b}{\tan\beta^2}\right) + hb\bar{b}\,\frac{1}{\cos\beta}\left(1-\frac{\Delta m_b}{\tan\alpha\tan\beta}\right)\Bigg]
\end{aligned}
$$

…

- Input parameters for relic density module are physical parameters of SHLA, flexibility: any model for which the MSSM spectrum can be calculated with an external code can be incorporated easily
- Input parameters to micromegas can be specified at the weak scale or at the GUT scale using some spectrum calculator program (default is SUSPECT) , includes mSUGRA, non-univ. SUGRA, AMSB
- CalcHEP is included: computes all cross-sections for 2->2 processes in SUSY and all 1-> 2 decays in SUSY
- Interactive link to CalcHEP
- Package include other constraints
  - b->s gamma (NLO) , $(g-2)_\mu$ $B_s \to \mu\mu$, $\Delta\rho$


SUGRA
(5 parameters)
AMSB
MSSM
19 parameters
“soft terms”
Spectrum calculation
SUSPECT
SOFTSUSY
SPHENO
Isajet
Spectrum calculation
-Tree-level
-Rad cor to mass
SUSPECT
ISAJET
SUSY Les Houches Accord
Physical parameters of MSSM:
Masses and mixings
micrOMEGAs
Calculation of all annihilation and coannihilation cross-sections And Relic density

Comparaisons:
micrOMEGAs1.3 / Darksusy4.0

- Extensive checks with DarkSUSY_4.0, now in very good agreement, some differences at large tanβ (due to Δm_b corrections)

name	M_0	$M_{1/2}$	A_0	$\tan\beta$	$sgn(\mu)$	micrOMEGAs1.3	DarkSUSY4.0
A	107	600	0	5	1	0.0944	0.0929
B	57	250	0	10	1	0.124	0.121
C	80	400	0	10	-1	0.117	0.115
D	101	525	0	20	1	0.0876	0.0864
G	113	375	0	20	1	0.133	0.129
H	244	935	0	20	1	0.166	0.163
I	181	350	0	35	1	0.142	0.132
J	299	750	0	35	1	0.102	0.0975
K	1001	1300	0	46	-1	0.0893	0.0870
L	303	450	0	47	1	0.114	0.0982

- Difference when LSP~10TeV

```
sugomg 107 600 0 5 1
```

will produce the following output:

```
Higgs masses and widths
h   : Mh    =  116.0 (wh    =2.5E-03)
H   : MHH   =  899.2 (wHh   =1.9E+00)
H3  : MH3   =  898.5 (wH3   =2.2E+00)
H+  : MHc   =  902.0 (wHc   =2.3E+00)

Masses of SuperParticles:
~o1 : MNE1  =   249.1 || ~l1 : MSl1  =   254.2 || ~eR : MSeR  =   256.0
~mR : MSmR  =   256.0 || ~nl : MSnl  =   413.1 || ~ne : MSne  =   413.4
~nm : MSnm  =   413.4 || ~eL : MSeL  =   420.2 || ~mL : MSmL  =   420.2
~l2 : MSl2  =   420.4 || ~1+ : MC1   =   468.3 || ~o2 : MNE2  =   468.5
~o3 : MNE3  =   780.0 || ~2+ : MC2   =   793.2 || ~o4 : MNE4  =   794.3
~t1 : MSt1  =   946.7 || ~b1 : MSb1  =  1153.1 || ~b2 : MSb2  =  1187.8
~dR : MSdR  =  1188.4 || ~sR : MSsR  =  1188.4 || ~t2 : MSt2  =  1190.6
~uR : MSuR  =  1194.8 || ~cR : MScR  =  1194.8 || ~uL : MSuL  =  1248.2
~cL : MScL  =  1248.2 || ~dL : MSdL  =  1250.5 || ~sL : MSsL  =  1250.5
~g  : MSG   =  1358.1 ||
Xf=2.67e+01 Omega=8.87e-02
```

```
Channels which contribute to 1/(omega) more than 1%.
Relative contrubutions in % are displyed
  1% ~o1 ~o1 -> l L
  3% ~o1 ~l1 -> Z l
 12% ~o1 ~l1 -> A l
  2% ~o1 ~eR -> Z e
  8% ~o1 ~eR -> A e
  2% ~o1 ~mR -> Z m
  8% ~o1 ~mR -> A m
 11% ~l1 ~l1 -> l l
  2% ~l1 ~L1 -> A Z
  3% ~l1 ~L1 -> A A
  8% ~eR ~l1 -> e l
  6% ~eR ~eR -> e e
  1% ~eR ~ER -> A Z
  2% ~eR ~ER -> A A
  6% ~eR ~mR -> e m
  8% ~mR ~l1 -> m l
```

```
deltartho=9.11E-06
gmuon=3.12E-10
bsgnlo=3.85E-04
bsmumu=3.13E-09
MassLimits OK
```

```
Example of some cross sections and widths calculation
  for mSUGRA point m0=107.0,mhf=600.0,a0=0.0,tb=5.0

 Z partial widths
  b   B - 3.684E-01 GeV
  d   D - 3.703E-01 GeV
  u   U - 2.873E-01 GeV
  c   C - 2.873E-01 GeV
  s   S - 3.703E-01 GeV
  l   L - 8.378E-02 GeV
 nl  Nl - 1.670E-01 GeV
 nm  Nm - 1.670E-01 GeV
 ne  Ne - 1.670E-01 GeV
  m   M - 8.397E-02 GeV
  e   E - 8.397E-02 GeV
Total 2.436E+00 GeV
```

All tree-level widths , MS+SUSY

All 2→2 cross-sections

```
Cross sections at Pcm=500.0 GeV
e,E->~1+,~1-
e,E->~1+(468),~1-(468)  is 7.135E-03 pb
e,E->~o1,~o2
e,E->~o1(249),~o2(468)  is 1.130E-02 pb
```

Download

- Current version micromegas_1.3.6 can be found at
  - http:://wwwlapp.in2p3.fr/lapth/micromegas
  - For help : micro.omegas@lapp.in2p3.fr
- Interactive web page for mSUGRA model (includes comparison of Isajet/SoftSUSY/Spheno/Suspect)
  - http://cern.ch/kraml/comparison
- Modular system, easily extendable to other models using LanHEP+ CalcHEP

NMSSM

- MSSM with additional singlet superfield

$$
\begin{aligned}
-\mathcal{L}_{\text{soft}} &= m_{\text{H}_\text{u}}^2 |H_u|^2 + m_{\text{H}_\text{d}}^2 |H_d|^2 + m_{\text{S}}^2 |S|^2 \\
&+ (\lambda A_\lambda H_u H_d S + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}) \\
&- \frac{1}{2}\left(M_2 \lambda_2 \lambda_2 + M_1 \lambda_1 \lambda_1 + \text{h.c.}\right) .
\end{aligned}
$$

- Higgs sector: 3 scalars, 2 pseudoscalars

- Neutralino sector: 5 neutralinos

$$
\begin{pmatrix}
M_1 & 0 & M_Z \sin\theta_W \sin\beta & -M_Z \sin\theta_W \cos\beta & 0 \\
0 & M_2 & -M_Z \cos\theta_W \sin\beta & M_Z \cos\theta_W \cos\beta & 0 \\
M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & 0 & -\mu & -\lambda v \cos\beta \\
-M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & -\mu & 0 & -\lambda v \sin\beta \\
0 & 0 & -\lambda v \cos\beta & -\lambda v \sin\beta & 2\nu
\end{pmatrix}
$$

Implementation into micrOMEGAs

- LanHEP: from the Lagrangian writes all masses and couplings in CompHEP/CalcHEP notation
- Higgs sector: write effective potential

$$
\begin{aligned}
V_{\rm rad} \;=\;& \lambda_1(H_uH_u^*)^2/2+\lambda_2(H_dH_d^*)^2/2+\lambda_3(H_uH_u^*)(H_dH_d^*)\\
+\;& \lambda_4(\epsilon H_uH_d)(\epsilon H_u^*H_d^*)+\lambda_5((\epsilon H_uH_d)^2+(\epsilon H_u^*H_d^*)^2)/2\\
+\;& \lambda_1^s(H_uH_u^*)SS^*+\lambda_2^s(H_dH_d^*)SS^*+\lambda_s^s(SS^*)^2/2\\
+\;& \lambda_5^s((\epsilon H_uH_d)S^2+(\epsilon H_u^*H_d^*)S^{*2})/2+\lambda_p^s(S^4+S^{*4})\,.
\end{aligned}
$$

- New couplings must be calculated by an external program
  - We use NMHDECAY to calculate Higgs masses and mixings, U. Ellwanger, J. Gunion, C. Hugonie, JHEP02(2005)066
  - From this extract λ's and calculate Higgs self-couplings

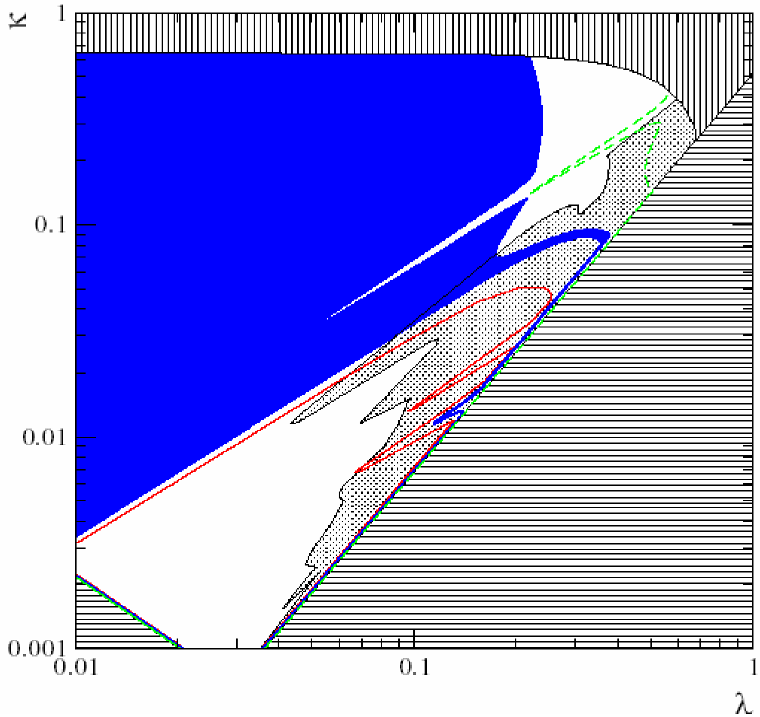
micromegas_nmssm

- CalcHEP calculates all necessary cross-sections
- Computation of relic density within micrOMEGAs:
  - Input parameters : SLHA_nmssm
  - Masses/mixings of Higgses: from NMHDECAY
  - Other susy masses: calculated at tree-level from the soft terms
  - As in MSSM: solve evolution equation, include all coannihilation channels, improved width for Higgs (e.g. Hff), careful treatment of poles
  - Also calculates all 2-2 cross-sections and 1->2 decays (tree-level)
  - LEP constraints given by NMHDECAY
  - Other routines such as b-sgamma not implemented yet (will do through NMHDECAY)
- Available on NMHDECAY web page :
  - http://www.th.u-psud.fr/NMHDECAY/
- Soon on http://wwwlapp.in2p3.fr/lapth/micromegas
  - GB, Boudjema, Hugonie, Pukhov, Semenov, hep-ph/0505142

Some results

- As in the MSSM, WMAP favours models with LSP mixed bino/Higgsino
  - Main annihilation ->WW,tt
- What's different:
- Annihilation into light Higgses (scalar or pseudoscalar)
- More resonances
  - Even at low tanβ
  - Can be h2,a1 …
- Singlino LSP: can be compatible with WMAP
  - Annihilation near resonance, annihilation into Higgses

μ=220, M_2=320, tanβ=5, A_λ =500, A_κ=0



G.B. et al, hep-ph/0505142

New developments: micromegas_2.0

- A generic program to calculate the relic density of DM in any model
- Assume some " R-parity " and particles either odd/even under this parity
- Need to specify all couplings in CalcHEP (CompHEP) notation
- Must provide masses of all particles

- Code then automatically looks for "LSP" and for resonances
- Computes all annihilation and coannihilation cross-sections
- Solves the evolution equation and obtains the relic density
- Other constraints must be provided by user in fortran or C routine

- A working example: micromegas_nmssm
- Under development:
  - UED (Csaba Balazs, et al)
  - Warped Xtra-Dim (G. Servant + micromegas)

New developments: Indirect detection

- Pair of dark matter particles annihilate and their annihilation products are detected in space – possibly signal for dark matter
  - Positrons from neutralino annihilation in the galactic halo
  - Photons from neutralino annihilation in center of galaxy
  - Neutrinos from neutralino in sun

- Module being finalised: photons (with S. Rosier-Lees, P. Brun)
  - "hard" photon line from loop processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma$
    - F. Boudjema, A. Semenov, D. Temes, hep-ph/0507127
    - Agrees with PLATON, DarkSUSY (except for γZ)
  - Continuum from pair of neutalinos into b,t,W,Z,h…
    - Use PYTHIA for photon spectrum

Annihilation into photons: comparison

	Sugra	nSugra	higgsino-1	higgsino-2	wino-1	wino-2
M_1	0.2	0.1	0.5	20.	0.5	20.0
M_2	0.4	0.4	1.0	40.	0.2	4.0
μ	1.0	1.0	0.2	4.0	1.0	40.0
M_A	1.0	1.0	1.0	10.	1.0	10.0
$m_{\tilde{f}}$	0.8	0.8	0.8	10.	0.8	10.0
Ωh^2	5.31	18.8	$6.41\ 10^{-3}$	1.59	$1.16\ 10^{-3}$	0.46
$\sigma v_{\gamma\gamma} \times 10^{27}$						
v=0	$5.82\ 10^{-5}$	$1.58\ 10^{-5}$	$7.01\ 10^{-2}$	$4.71\ 10^{-2}$	1.99	1.52
PLATONdml	$5.82\ 10^{-5}$	$1.58\ 10^{-5}$	$7.01\ 10^{-2}$	$4.72\ 10^{-2}$	1.99	1.53
DarkSUSY	$5.81\ 10^{-5}$	$1.58\ 10^{-5}$	$7.02\ 10^{-2}$	$4.71\ 10^{-2}$	1.99	1.52
$\sigma v_{Z\gamma} \times 10^{27}$						
v=0,full	$2.03\ 10^{-5}$	$2.61\ 10^{-6}$	$2.19\ 10^{-1}$	$2.20\ 10^{-2}$	11.7	10.1
v=0,part	$1.94\ 10^{-5}$	$2.50\ 10^{-6}$	$2.61\ 10^{-1}$	$3.29\ 10^{-2}$	11.7	10.1
DarkSUSY	$1.42\ 10^{-5}$	$1.79\ 10^{-6}$	$2.61\ 10^{-1}$	$3.29\ 10^{-2}$	11.7	10.1

Outlook and conclusion

- Future plans:
  - Expand indirect detection to include positrons, antiprotons, neutrinos
  - Direct detection

- *Flexible and extendable package to calculate relic density in the MSSM and its extensions*
- *Includes constraints on MSSM and provides tree-level cross-sections and decay widths*

- Current version micromegas_1.3.6 can be found at
  - http:://wwwlapp.in2p3.fr/lapth/micromegas