Neutralino Dark Matter and SUSY Spectroscopy

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June 2004
YITP - 2004

The prediction of cosmic dark matter is an important argument for the presence of SUSY in Nature.

This is a robust prediction of the theory, requiring only the stability of neutralinos,

a consequence of R-parity and mass relations such as

$$m_N < m(\widetilde{\ell})$$

This success of SUSY was recognized very early in the phenomenological study of the theory by Weinberg, Ellis, Goldberg, and others.

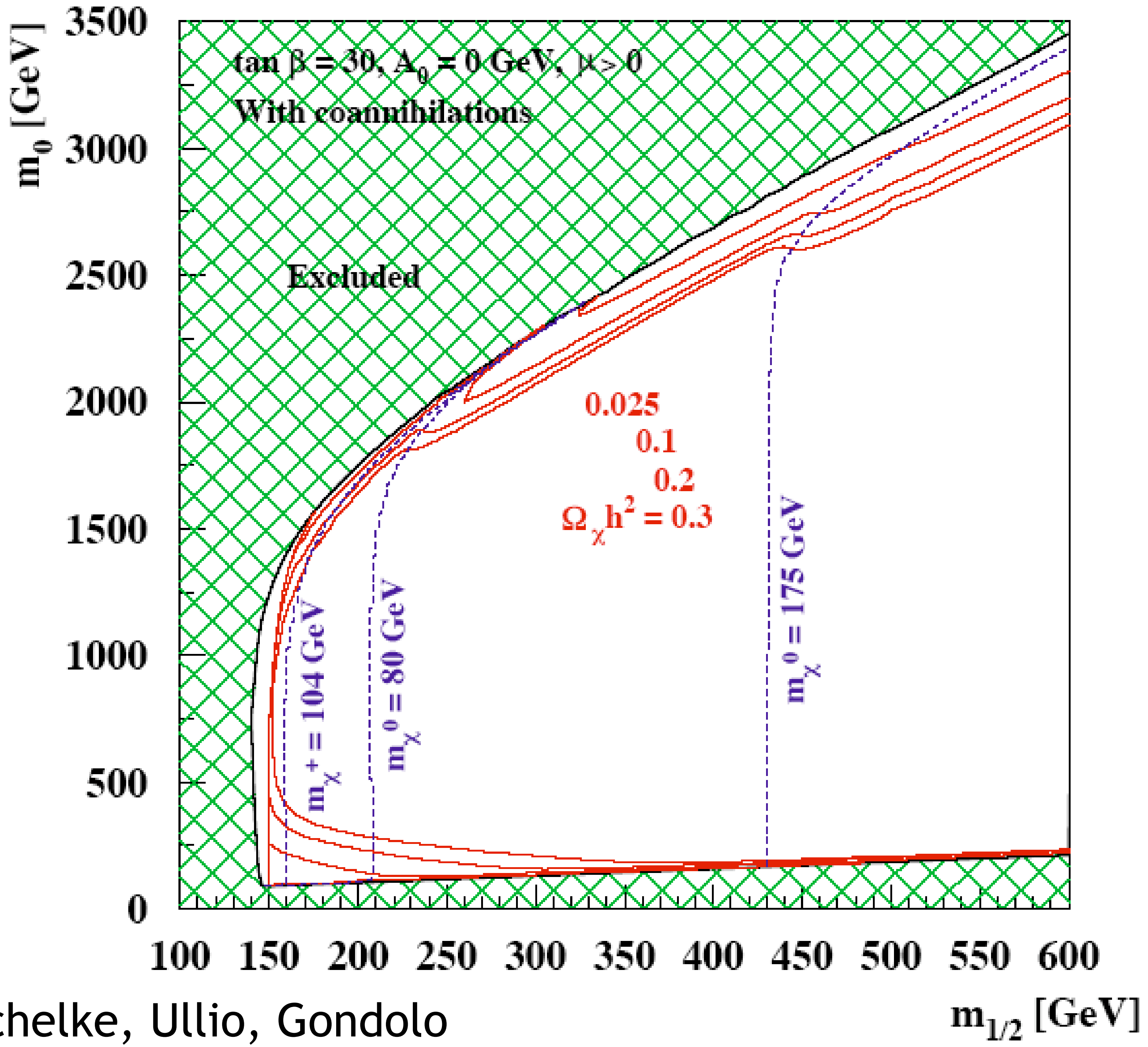
Now the WMAP experiment has given us a very accurate value of the cosmic density of non-baryonic dark matter:

$$\Omega_N h^2 = 0.113 \pm 0.009$$

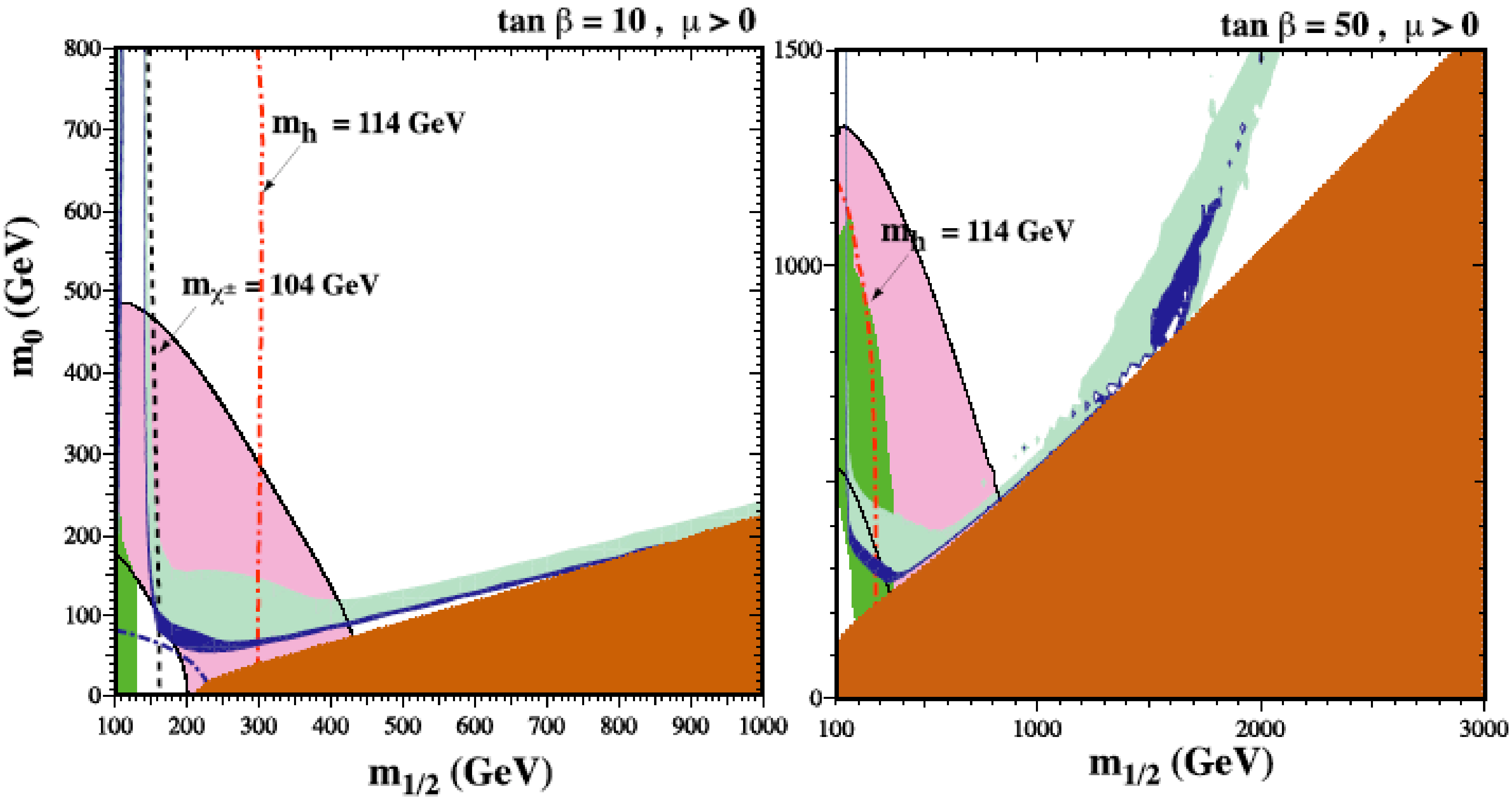
The Planck satellite will give even higher precision.

Advocates of SUSY should consider this value as a important constraint on the SUSY parameter space.
Can it be accomodated ?

It turns out that this is quite nontrivial. In the conventional SUSY parameter space ("constrained minimal supergravity") ➤



Edsjo, Schelke, Ullio, Gondolo



Ellis, Olive, Santoso, Spanos

In this lecture, I would like to present my point of view on this problem.

I am not a technical expert in SUSY dark matter. But I think that I can bring to the subject some insight into the particle physics aspects of SUSY that might help to clarify where we stand.

Related work by

Birkedal-Hansen, Matchev, Battaglia, Belanger

is part of the ongoing LC + Comology study (Feng/Trodden)

Connections between LHC physics and SUSY dark matter have been studied by Drees and Nojiri.

I will concentrate on the prediction of the density of the neutralino as a thermal relic. That is, I assume that the neutralino was once in thermal equilibrium, and that evolution of its Boltzmann equation from that point determines its current density.

Even in SUSY, we can have theories of the dark matter relic density outside this picture:

nonthermal production	Moroi-Randall
decay of N to "super-WIMP"	Feng-Takayama-Rajaraman

But, only the thermal relic picture

clearly motivates $m_N \sim 100\ \mathrm{GeV}$

allows precise confrontation of microscopic measurements with Ω_N.

Basic formulae for thermal dark matter

(Turner-Scherrer approximation)

freeze-out: $\xi = T_f / m_N \sim 1/25$

then $$\Omega h^2 = \frac{s_0}{\rho_c / h^2} \left(\frac{45}{\pi g_*} \right)^{1/2} \frac{1}{m_{\rm Pl}} \frac{1}{\langle \sigma v \rangle}$$

putting in numbers:
$$\Omega h^2 = 0.1 \to \langle \sigma v \rangle = 1 \text{ pb}$$

setting $\langle \sigma v \rangle = \frac{\pi \alpha^2}{8 m^2}$ we find m = 100 GeV,

making the connection between dark matter and the weak scale.

This argument leading to m(N) is quite general, not just restricted to SUSY.

It suggests a general line of argument that we should all be aware of:

Add one more assumption Tata

N is stable by virtue of a new quantum number carried by physics outside of the Standard Model.

Assume that there is a particle with color SU(3) that carries this new quantum number, and that this particle has a mass less than 2 TeV.

This assumption is realized in SUSY, in theories of TeV-scale extra dimensions, in most models with a new sector that explains Electroweak Symmetry Breaking.

The colored particle will be produced copiously at the LHC. Necessarily, it will decay to N, which exits an LHC detector unseen.

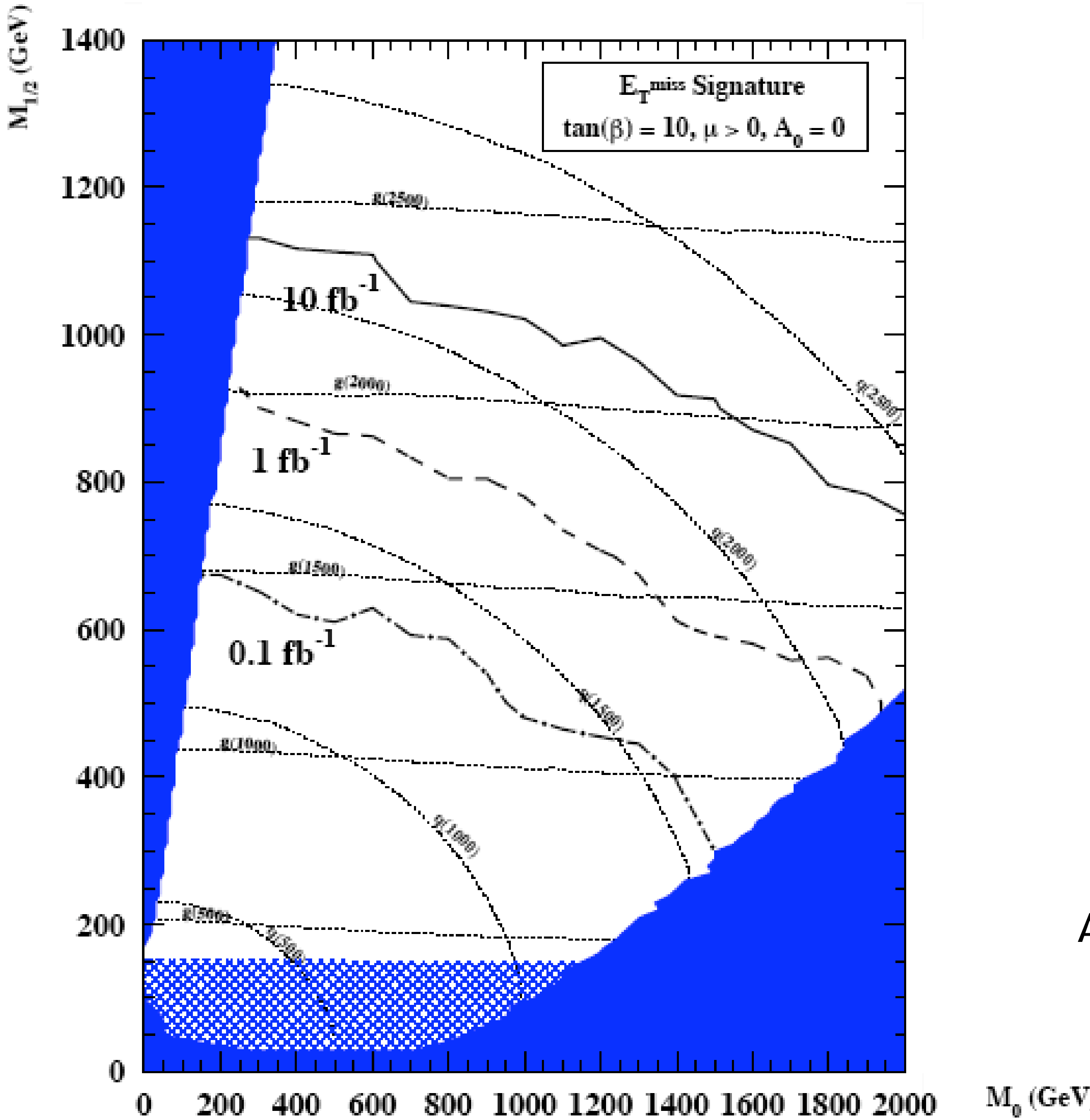
This reaction produces the familiar

$$\text{jets} + \text{missing } E_T$$

signature of SUSY, at the rate given by conventional expectation.

Dark matter tells us that we must see this physics at the LHC, whether there is SUSY in Nature or not.

Cheng, Matchev, Schmaltz



$M_{1/2}$ (GeV)
1400
1200
1000
800
600
400
200
0
E_T^{miss} Signature
tan(β) = 10, μ > 0, A_0 = 0
10 fb^{-1}
1 fb^{-1}
0.1 fb^{-1}
0
200
400
600
800
1000
1200
1400
1600
1800
2000
M_0 (GeV)

ATLAS

So, can we obtain $\langle \sigma v \rangle = 1 \text{ pb}$ in realistic SUSY models ?

Begin from the typical situation of MSUGRA models:

$$\mu \gg m_2 \sim 2m_1$$

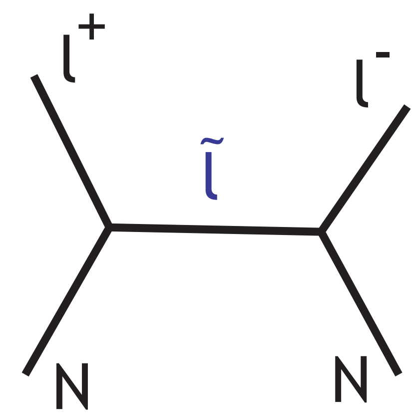
N is almost pure bino. Its dominant annihilation channels are

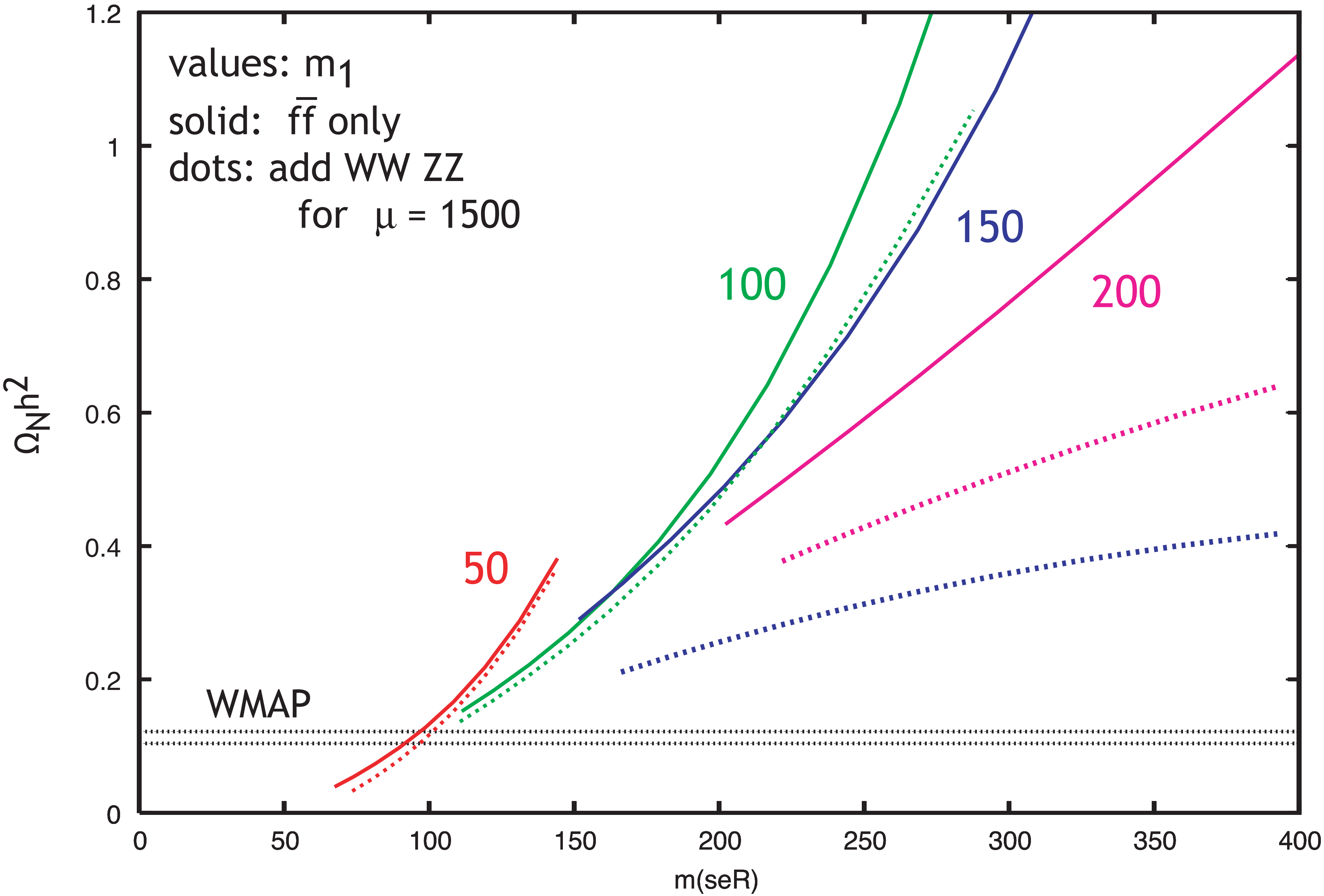
$$N \; N \to \ell^+ \ell^-, \; q\bar{q}$$

Goldberg: annihilation in the S-wave is helicity suppressed

but $\xi = \frac{T_f}{m_N} \sim \frac{1}{25}$

so ~ 8 x larger cross sections are needed





W-Y Chuang, E.-H.Yong, MEP

In the 1980's, $\Omega_N \sim 1$

it worked !

Today, $m_{\tilde{\ell}} > 100 \text{ GeV} \quad \Omega_N \sim 0.2$

it does not work any more (except for a range of slepton masses very close to the current limit).

Constrained MSUGRA makes it difficult to escape this region:

need heavy $\widetilde{t}$ to obtain large enough m_h, small enough corrections to $\Gamma(b \to s\gamma)$; this forces us to large $m(\widetilde{\ell})$

$\mu \sim m_2$ is obtained only in special regions

Nevertheless, the study of constrained MSUGRA has demonstrated some strategies for enhancing $\langle \sigma v \rangle$.

I prefer to look at this as follows:

Follow the regions of correct Ω through the larger MSSM parameter space. Hopefully, this will give more robust solutions.

Baer, Belayev, Krupovickas, Mustafayev have advocated adding a separate m_0^2 for the third generation.

More generally, we can vary the SU(2)XU(1) invariant soft masses, with degeneracy between 1st and 2nd generation to avoid flavor violation. In the examples here, I will impose gaugino unification: $2m_1 = m_2 = m_3/3.5$

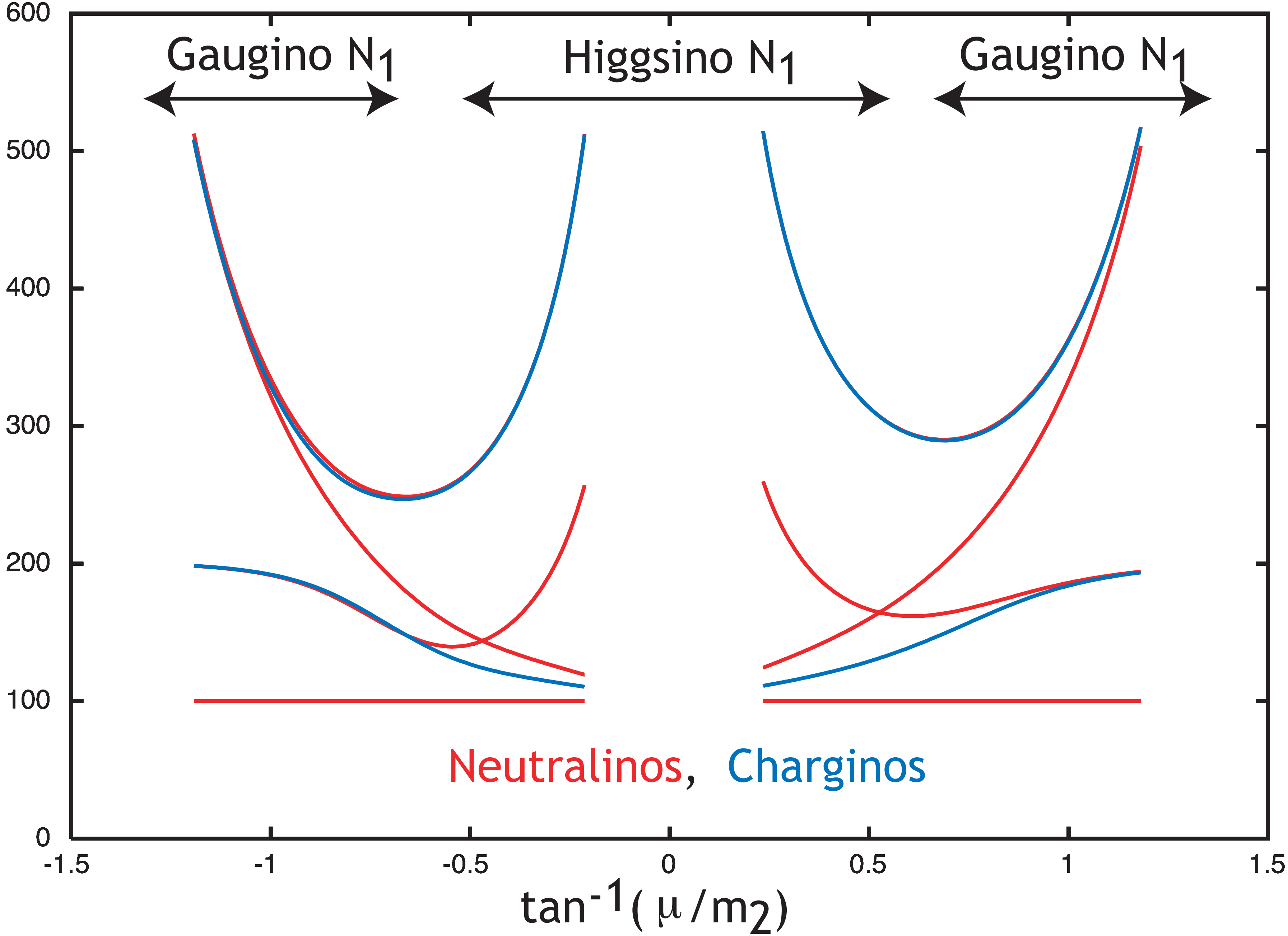
This is a space of 8-12 new parameters.

But, to the extent that specific annihilation channels dominate Ω_N , the relic density is insensitive to most of these parameters.

Strategies for enhancing $\langle \sigma v \rangle$:

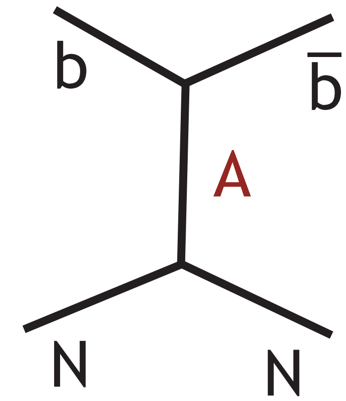
- Resonant enhancement
- $N \; N \to W^+ W^-$
- Co-annhilation

Some of the physics depends on the properties of neutralino eigenstates; recall these briefly ➤



600
500
400
300
200
100
0
Gaugino N1
Higgsino N1
Gaugino N1
Neutralinos, Charginos
-1.5
-1
-0.5
0
0.5
1
1.5
tan-1(μ /m2)

Resonant enhancement



CP, Majorana nature of N, imply

$N\ N \rightarrow A$ (only) in S-wave

The resonant cross section is

$$\langle \sigma v \rangle \sim \left(\frac{\pi \alpha^2}{8 m_N^2} \right) \cdot |\eta|^2 \cdot \left(\frac{m_b \tan\beta}{m_W s_w} \right)^2$$

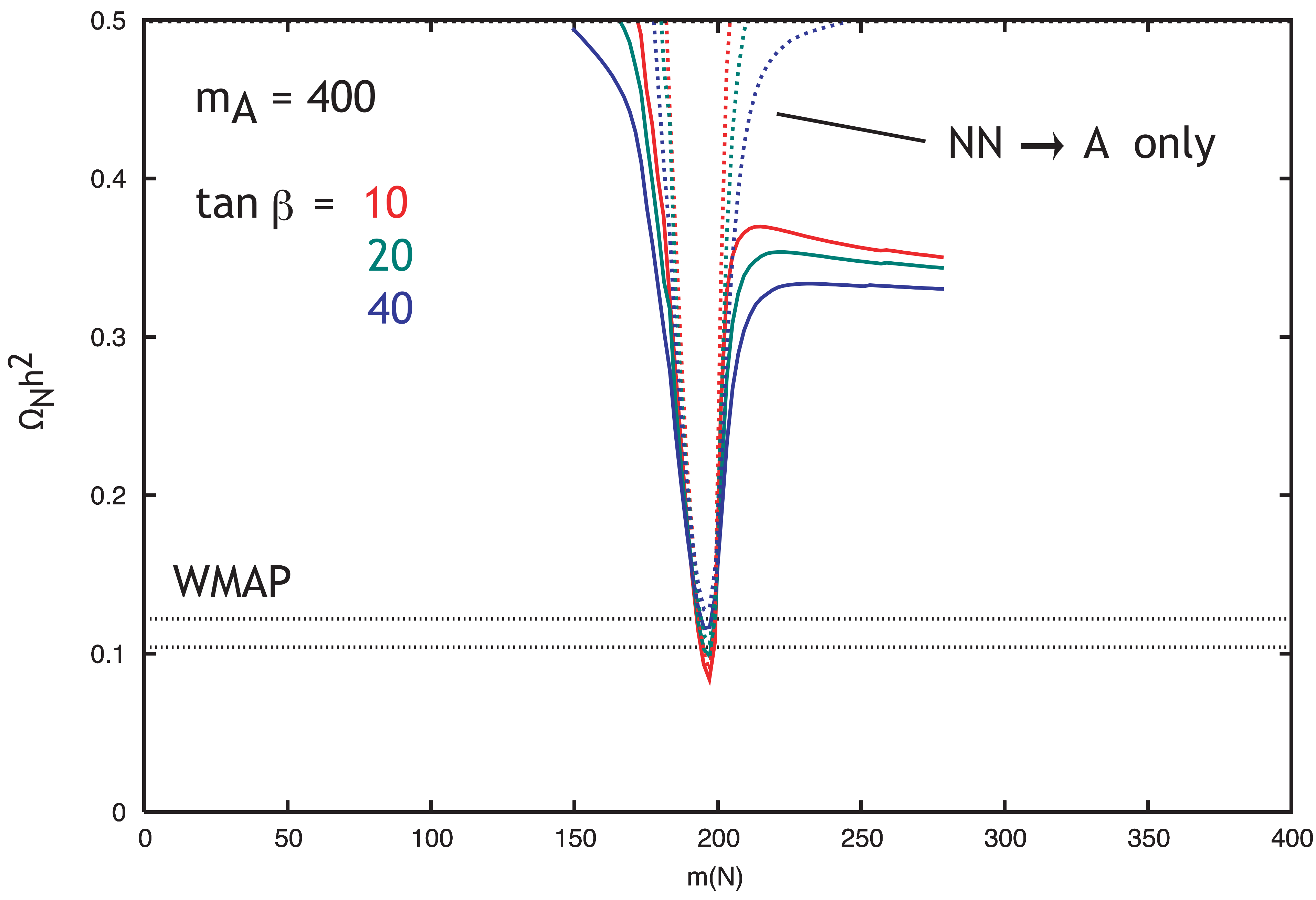
$$\cdot \left| \frac{4 m_N^2}{(4 m_N^2 - m_A^2) + i m_A \Gamma_A} \right|^2$$

η = Higgsino fraction in N

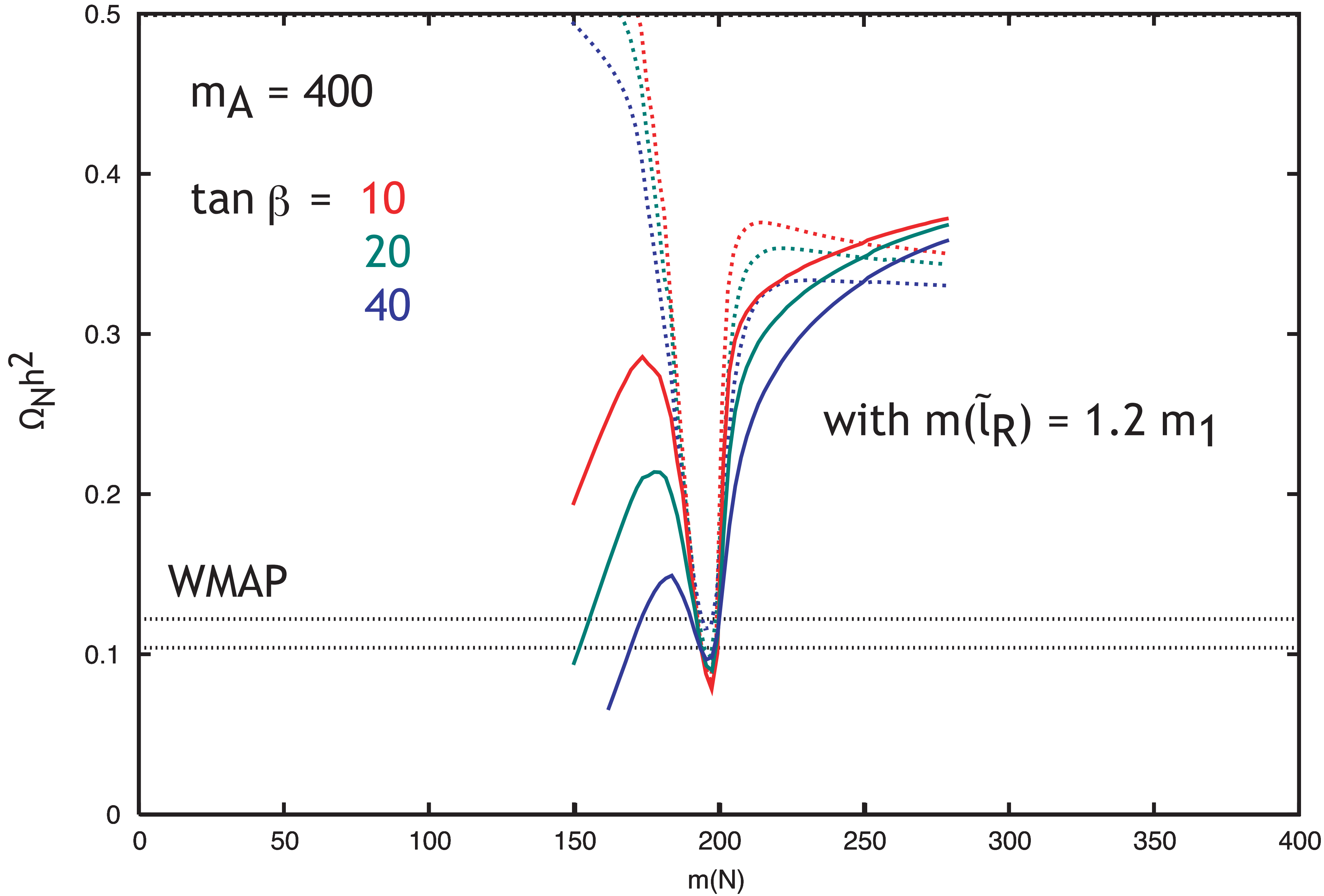
$m_b \tan\beta / m_W s_w \sim 1$ for $\tan\beta \sim 10$

$\Gamma_A / m_A \sim 1 - 2\%$

so the enhancement can be large even well off the peak.



m_A = 400
tan β = 10
20
40
NN → A only
WMAP
$\Omega_N h^2$
m(N)
0.5
0.4
0.3
0.2
0.1
0
0
50
100
150
200
250
300
350
400

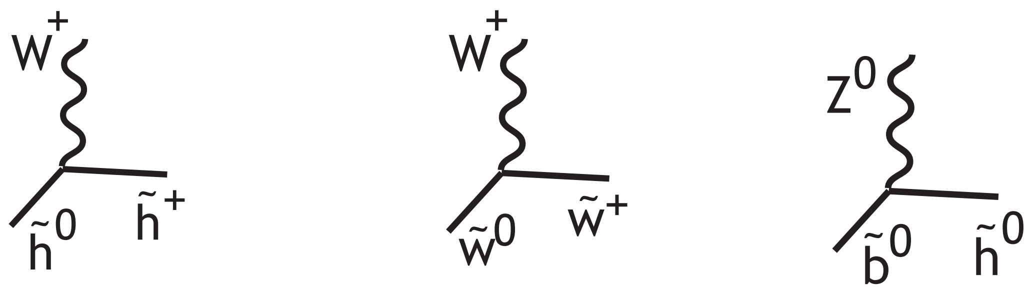


0.5
0.4
0.3
0.2
0.1
0
$\Omega_N h^2$
0
50
100
150
200
250
300
350
400
m(N)
m_A = 400
tan β = 10
20
40
with $m(\tilde{l}_R)$ = 1.2 m_1
WMAP

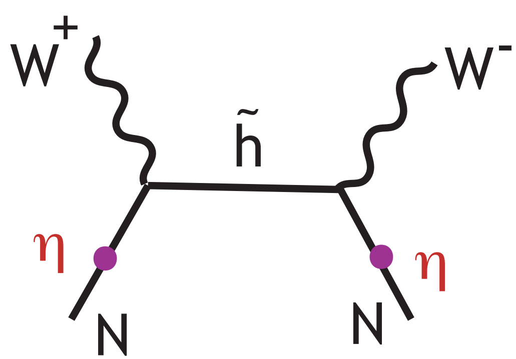
$N\ N \to W^+W^-$

$e^+e^- \to W^+W^-$ is the single process in e^+e^- annihilation with the largest cross section. We should try to take advantage of the analogous process for NN annihilation.

Once again, the process is suppressed for pure bino N:

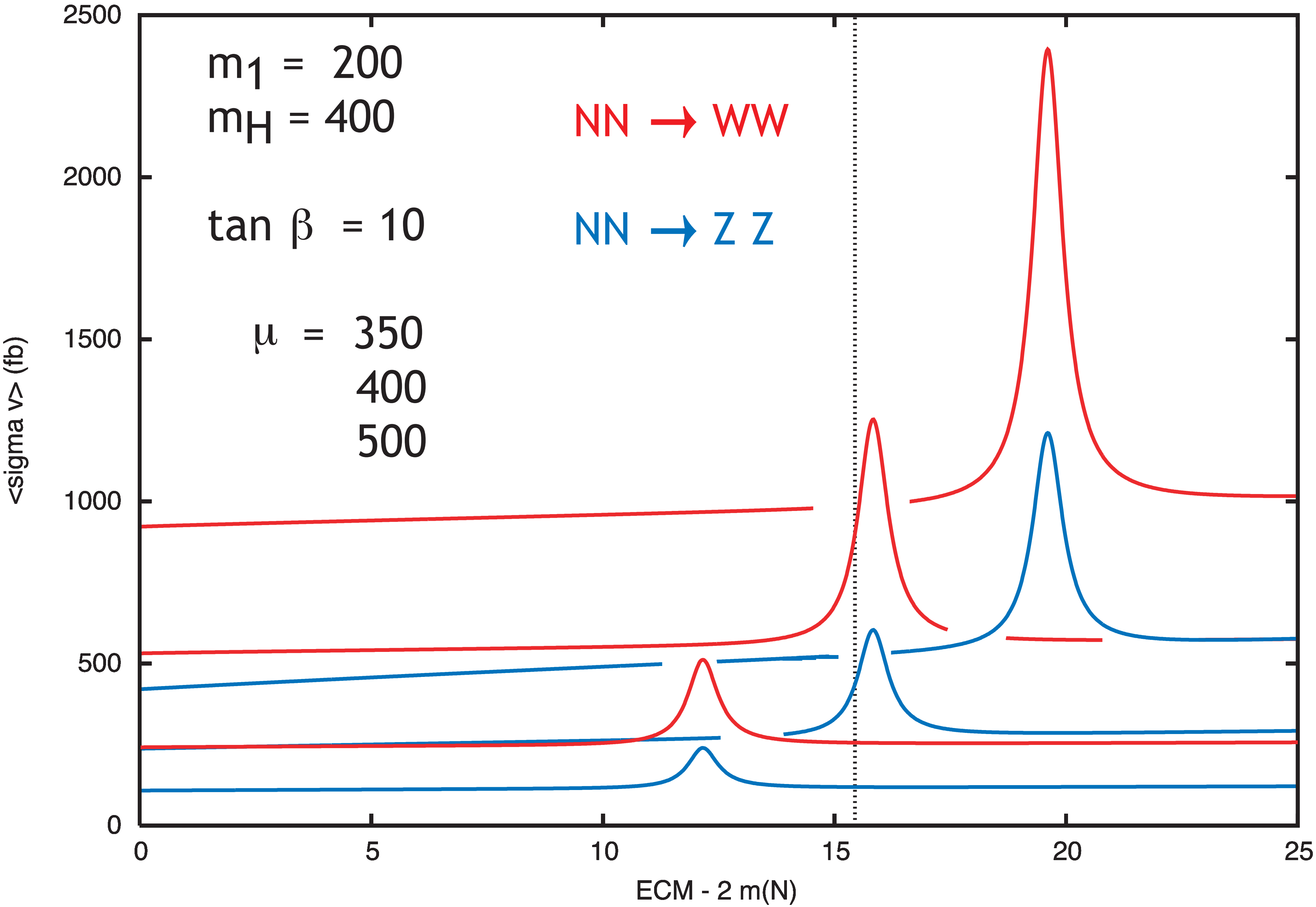


A picture of the physics is given by

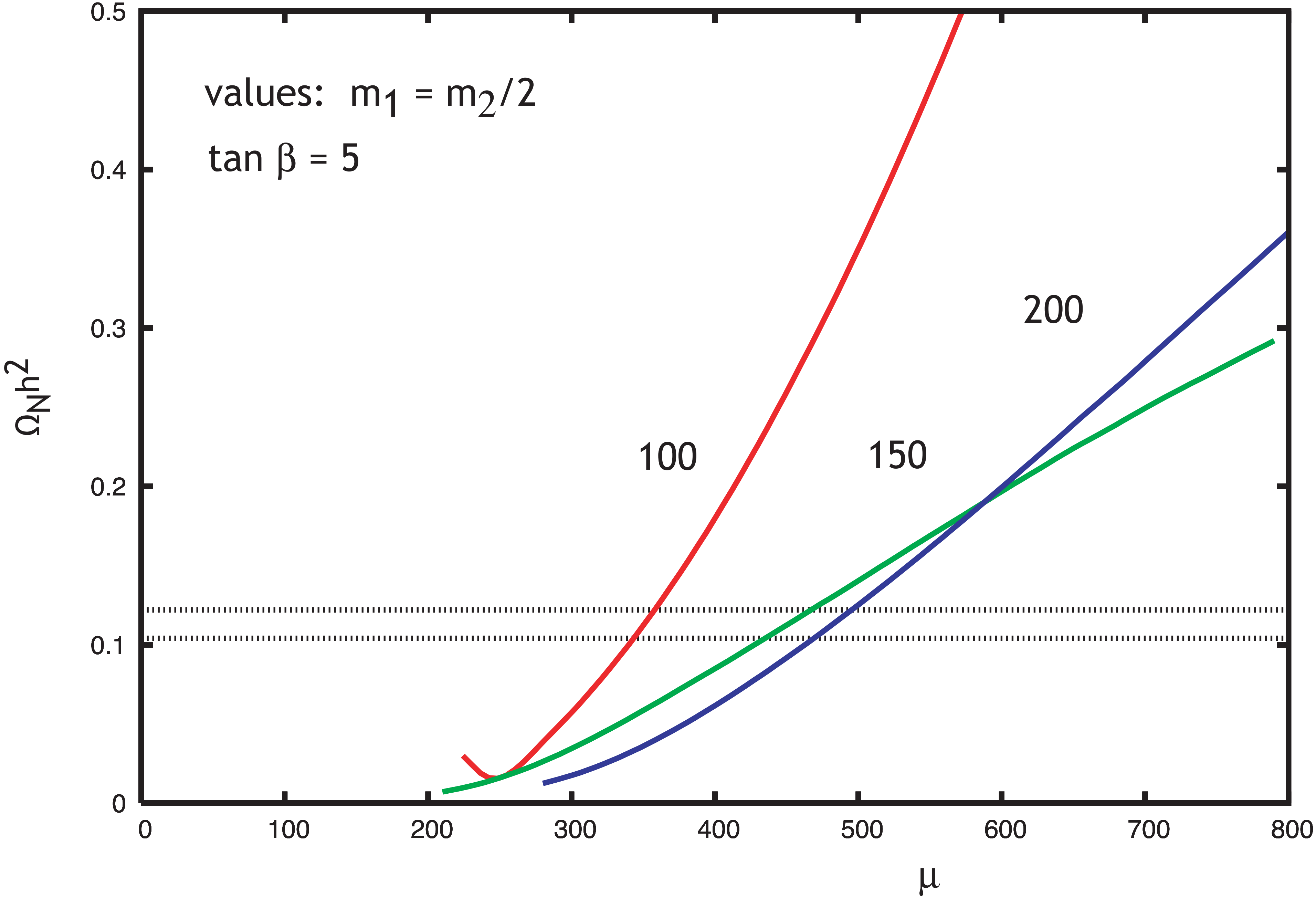


$\sim \quad \eta^2$

When $\mu < m_2$ (still $> m_1$), the C_1^+ becomes dominantly Higgsino and this gives a large enhancement.



m_1 = 200
m_H = 400
tan β = 10
μ = 350
400
500
NN → WW
NN → Z Z
2500
2000
1500
1000
500
0
0
5
10
15
20
25
<sigma v> (fb)
ECM - 2 m(N)



values: $m_1 = m_2/2$
$\tan\beta = 5$
100
150
200
$\Omega_N h^2$
μ
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
600
700
800

In constrained MSUGRA, this physics appears only in the "focus point" region.

For $m_t \sim 178\ \mathrm{GeV}$, the focus pont region appears at large scalar masses, $m_{\tilde{q}} > 7\ \mathrm{TeV}$

but $m_2, \mu \sim 200\ \mathrm{GeV}$ and the model is not especially fine-tuned.

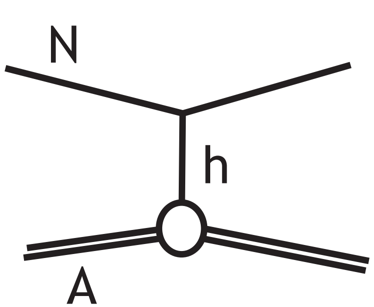
(Baer et al: find SUSY at LC, not at LHC, in this scheme)

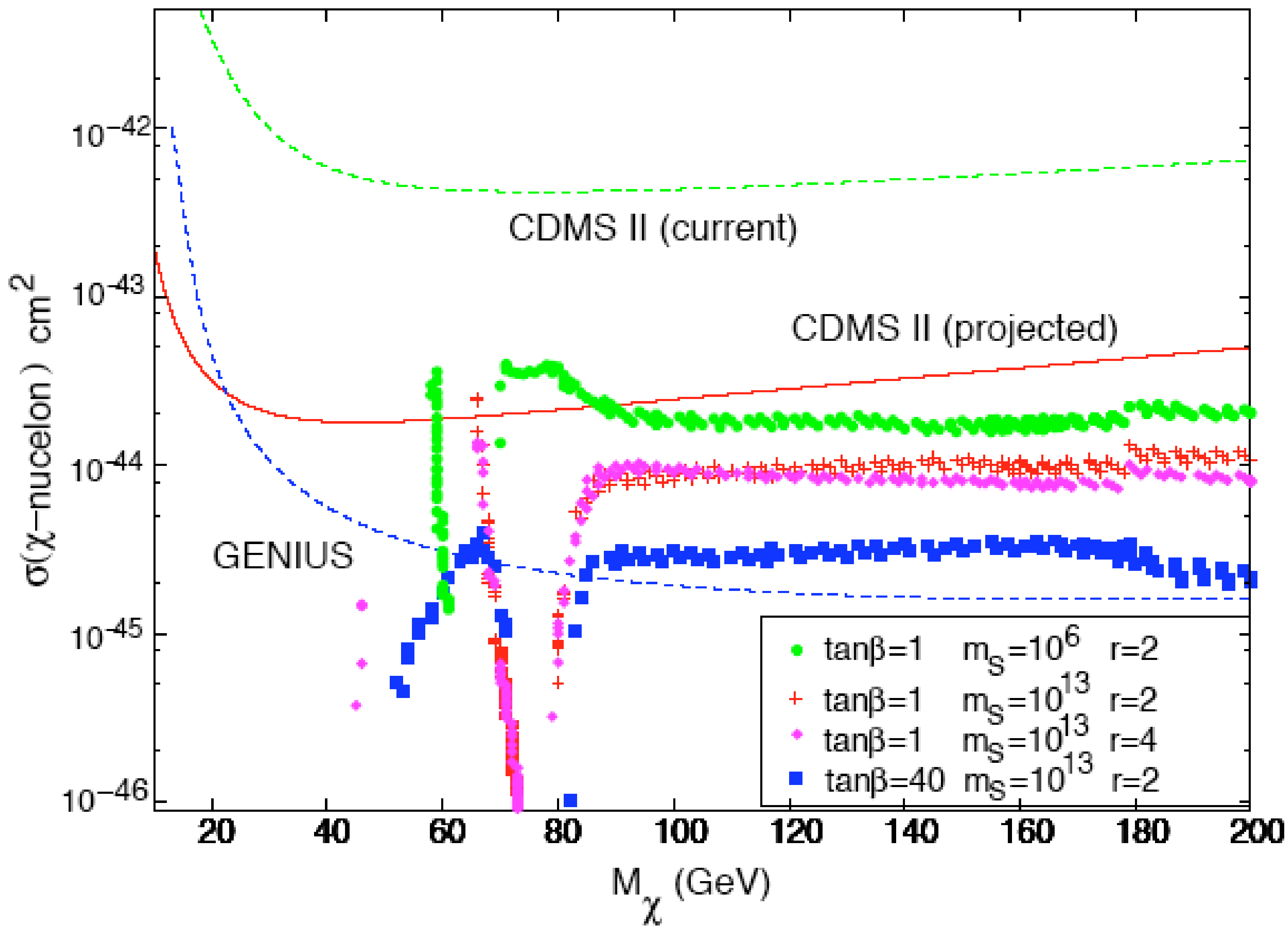
In the more general MSSM, this physics appears in a broader region.

Pierce: In much of this region, the direct-detection cross section for dark matter has a definite value

$$\sigma_{N-nucleon} \sim 10^{-44}\ \mathrm{cm}^2$$

accessible to future low background experiments.





CDMS II (current)
CDMS II (projected)
GENIUS
$\sigma(\chi\text{-nucleon})\ cm^2$
M_χ (GeV)
tanβ=1 $m_S=10^6$ r=2
tanβ=1 $m_S=10^{13}$ r=2
tanβ=1 $m_S=10^{13}$ r=4
tanβ=40 $m_S=10^{13}$ r=2

A. Pierce

Co-annihilation Greist, Seckel

In principle, many species carry R-parity. Transitions between species are mediated by light particles, which are plentiful in the thermal plasma

$$N + \ell^- \leftrightarrow \widetilde{\ell}^- + \gamma$$

So, relative densities are in thermal equilibrium

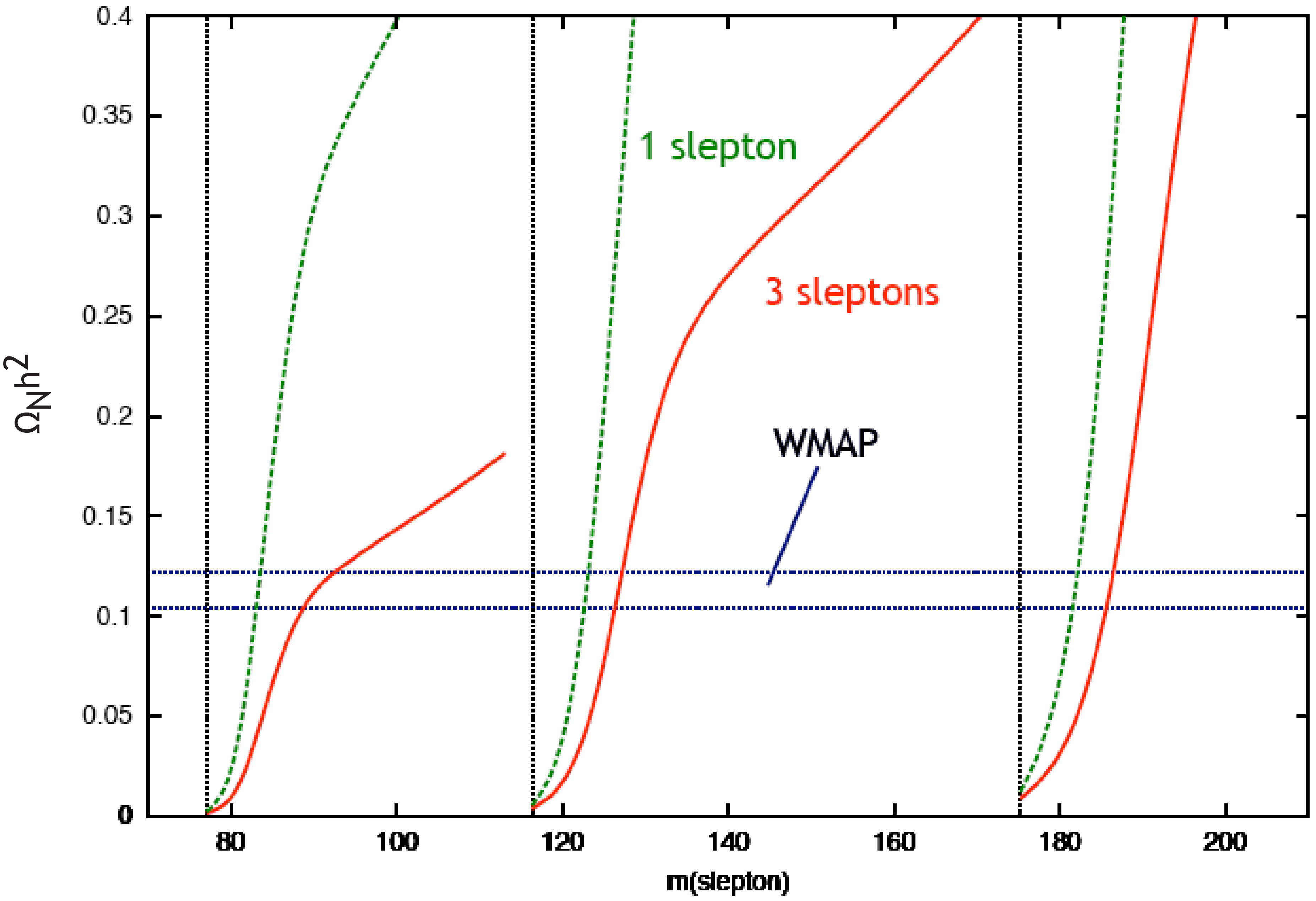
If $m_{\widetilde{\ell}} - m_N \sim T_f$ or $\frac{m_{\widetilde{\ell}} - m_N}{m_N} \sim \xi \sim 4\%$

then $n(\widetilde{\ell})$ is comparable to $n(N)$.

Some $\widetilde{\ell}$ processes, notably

$$\ell N \to \ell + \gamma, Z^0 \qquad \widetilde{\ell}^- \widetilde{\ell}^- \to \ell^- \ell^-$$

proceed in the S-wave. Then we can recover $\Omega h^2 \sim 0.1$ for m~ 100 GeV.



0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
$\Omega_N h^2$
80
100
120
140
160
180
200
m(slepton)
1 slepton
3 sleptons
WMAP

In constrained MSUGRA, the solutions to the problem of obtaining large enough $\langle \sigma v \rangle$ required very special choices of parameters. This is still a feature of these solutions in the general MSSM; we see a strong sensitivity to certain MSSM parameters.

This is an uncomfortable conclusion, but it also gives an opportunity:

Measure the parameters in accelerator experiments, confront the precise cosmological numbers with a precise microscopic prediction of the relic density.

This idea follows the "laboratory astrophysics" tradition of Fowler and Hoyle, with a step of

$$T \ \times 10^5 \qquad t \ \div 10^{10}$$

In each scenario, the sensitive parameters can be tied down by measurements of the spectroscopy:

resonance: $m_A \ , \quad \Gamma_A \ , \quad \Gamma(A \to b\bar{b})$

W^+W^- : $m(N_a) \ , m(C_b^+)$

slepton co-ann.: $m(\widetilde{\ell}) \ , \quad m(N)$

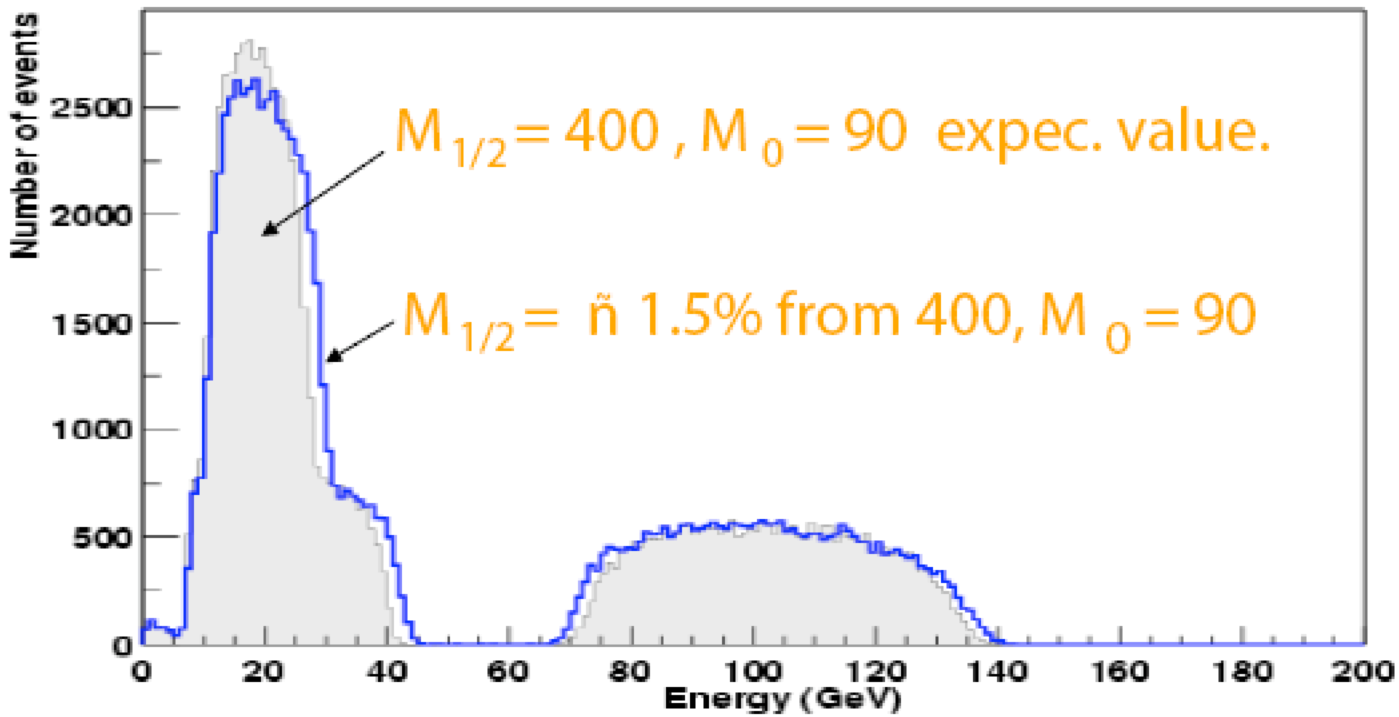
To match the precision from cosmology, we need parts-per-mil precision on these specific quantities.

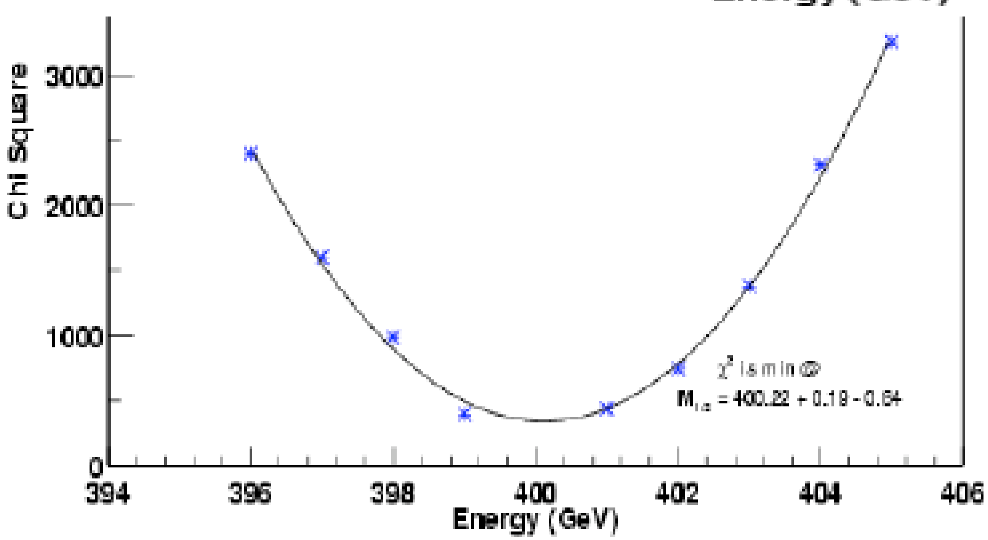
This goes far beyond the capabilities of the LHC and requires the specific advantages of the Linear Collider.

For the resonance case, separation of A from H properties may be too difficult in e^+e^- reactions; perhaps it is achievable in polarized $\gamma\gamma$ collisions

Asakawa et al.

500 GeV





Mass $\tilde{e}_R$ = 178.3 + 0.06 - 0.2
Mass $\tilde{e}_L$ = 287.1 + 0.1 - 0.6
Mass $\tilde{\chi}_1^0$ = 160.5 + 0.08 - 0.3

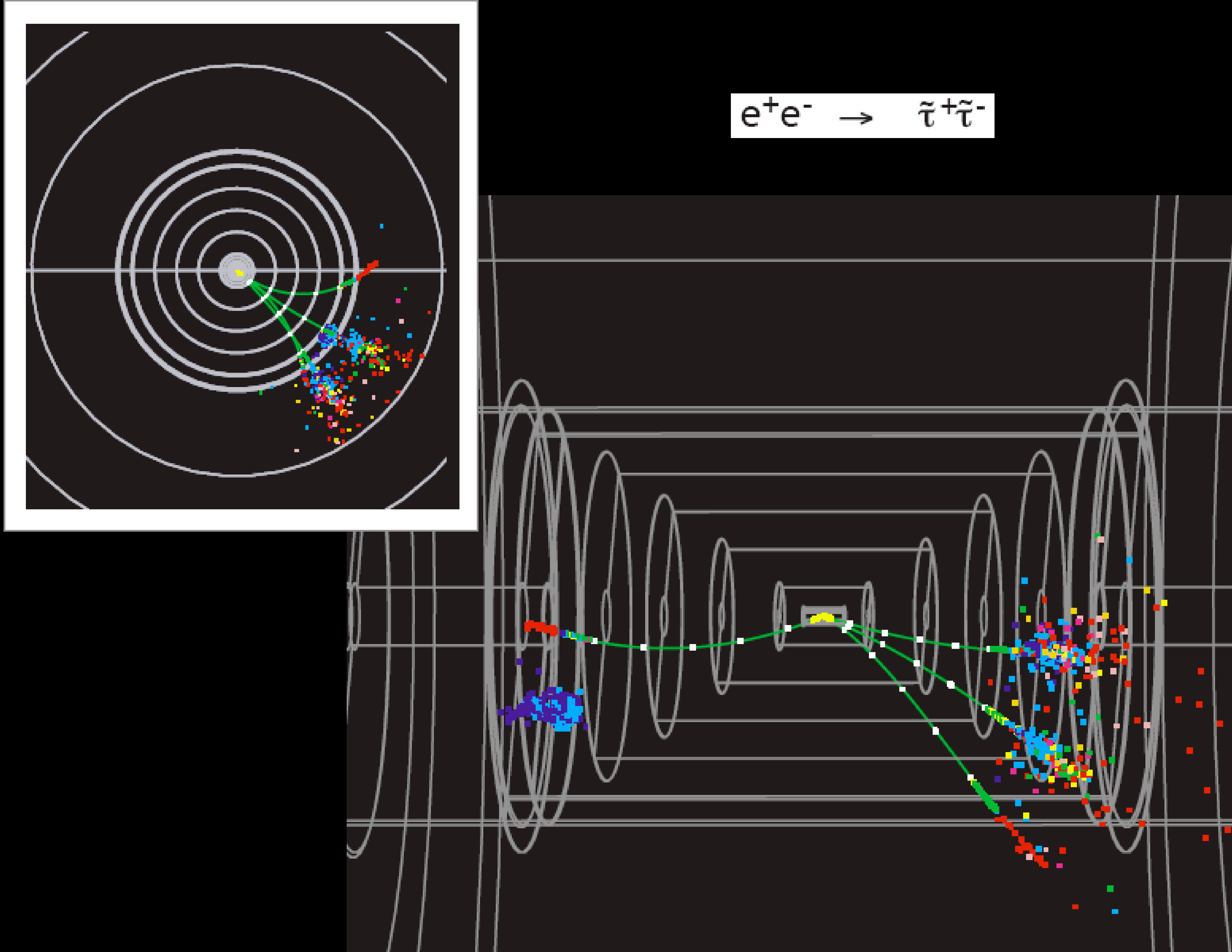
Nauenberg

In this talk, I have reviewed the implications for the SUSY spectrum of thermal neutralino dark matter.

Special properties of the spectrum are required, with a variety of scenarios,

Each leads to hopeful prospects for the detection and study of SUSY particles at colliders.

LHC and the Linear Collider will both have important roles. I believe that, in ten years, astrophysicists will give these facilities the same importance that our community now gives the new measurements in cosmology.


$e^+e^- \rightarrow \tilde{\tau}^+\tilde{\tau}^-$