Supersymmetric Dark Matter and Linear Collider Experiments

M. E. Peskin
April, 2004

From the beginning of the serious phenomenological study of SUSY, it has been recognized that SUSY has consequences for astrophysics and in particular for the problem of dark matter:

> We have a hint that photinos may provide an important ‘dark’ component to the cosmic mass density.
>
> -- S. Weinberg PRL 1983

Since that time, a huge literature has accumulated on the relation between SUSY and cosmic dark matter.

However, something is missing from this literature that ought instead to be emphasized:

a direct connnection between SUSY dark matter and
the capabilities of the Linear Collider

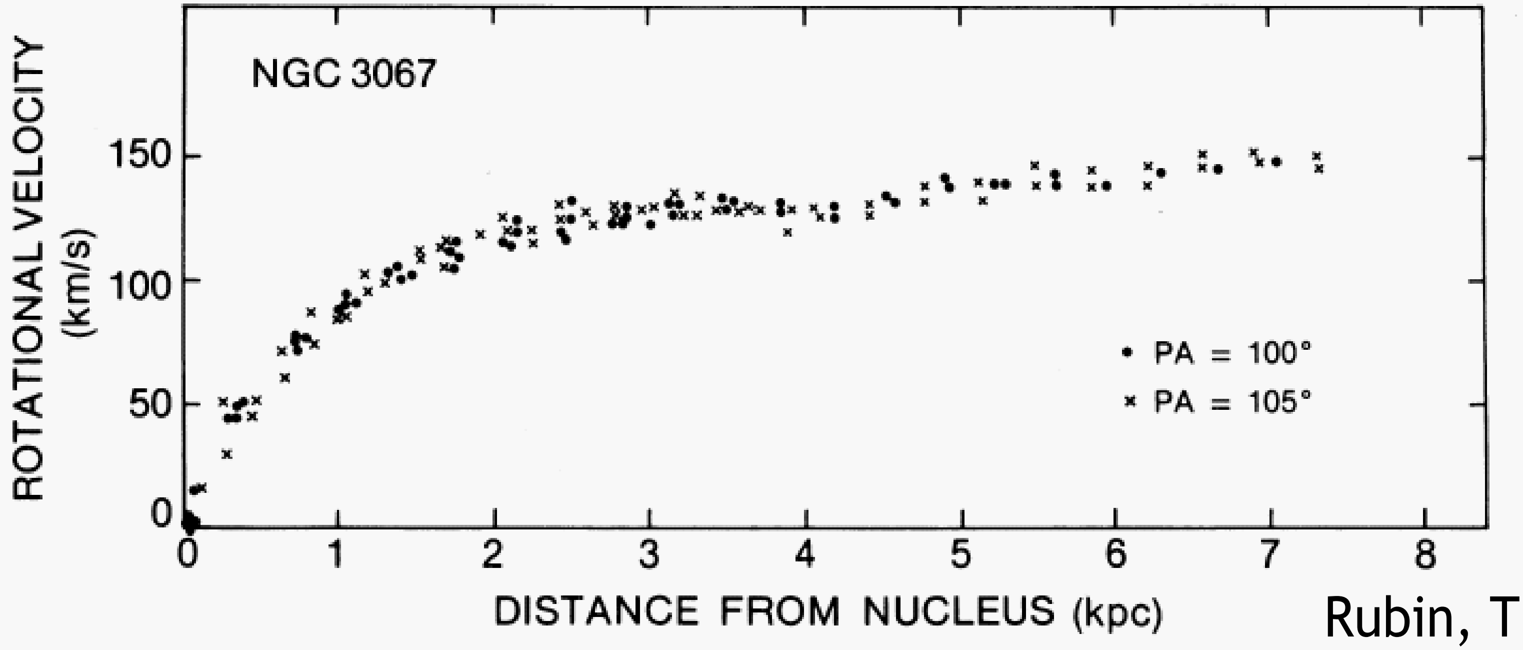
Recently, a group of us in the United States have been examining this issue as a part of a general study of relations between the LC and cosmology.

In this talk, I would like to

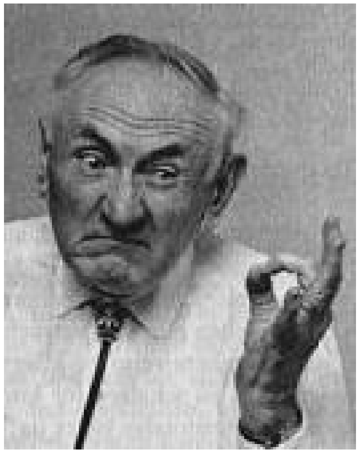
- give my personal viewpoint on this subject,
- describe the American LC group study aimed at making this connection more precise.

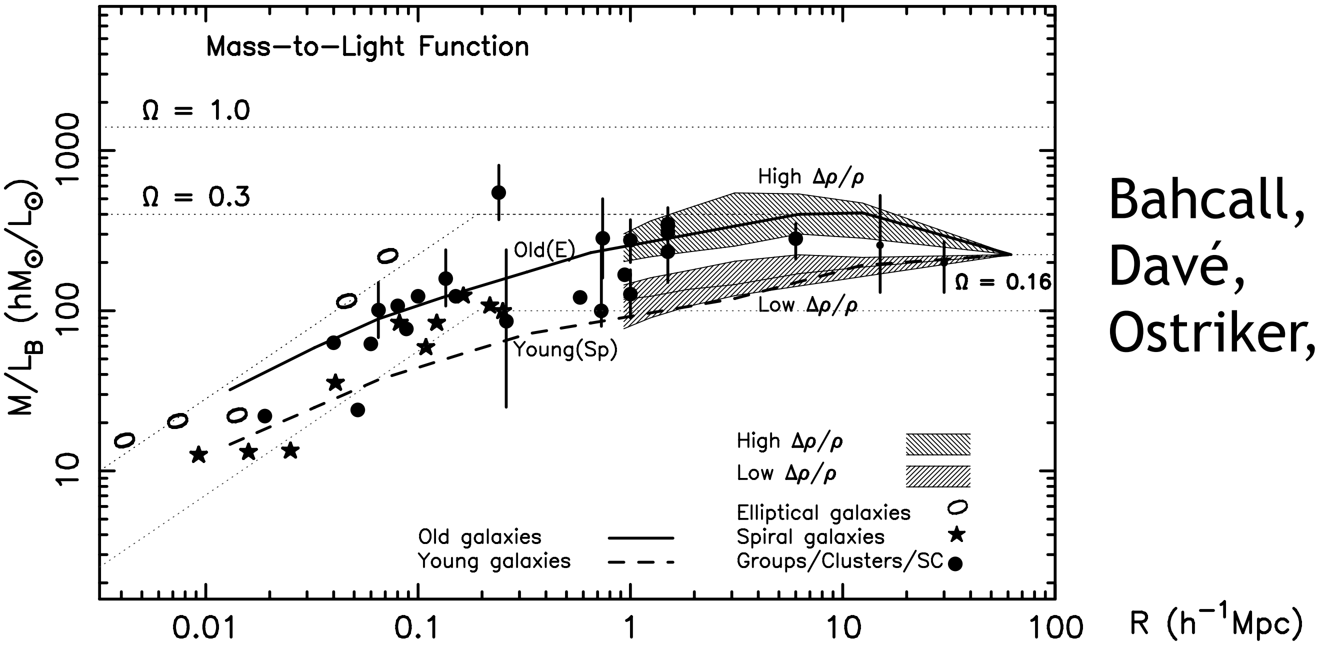
To begin, recall some general aspects of cosmic dark matter.

Dark matter is real, and is increasingly precisely measured....



Rubin, Thonnard, Ford





Bahcall, Cen, Davé, Ostriker, Yu

Most recently, measurement of the Cosmic Microwave Background fluctuations has given a very accurate estimate of the dark matter density:

$$\begin{aligned}\Omega_{tot} &= 1.02 \pm 0.02\\ \Omega_m h^2 &= 0.135 \pm 0.009\\ \Omega_b h^2 &= 0.0224 \pm 0.0009\end{aligned}$$

with $h = 0.72 \pm 0.05$ from the Hubble Space Telescope.

$\Omega_m - \Omega_b > 0$ requres a massive elementary particle not contained in the Standard Model.

It gives direct evidence for physics beyond the Standard Model.
This poses a problem and an opportunity for particle physics.

There are many hypotheses for the dark matter particle N, from the axion (10^{-3} eV) to the WIMPzilla (10^{18} GeV).

However, the most attractive idea is that N is a 'thermal relic particle': absolutely stable, in thermal equilibrium at high temperature, isolated by the expansion of the universe

In this class of models, it is possible to compute the density of N precisely from knowledge of the microscopic annihilation cross section

$$\Omega_N h^2 \approx \frac{s_0}{\rho_c/h^2}\left(\frac{45}{\pi g_*}\right)^{1/2}\frac{1}{m_{\rm Pl}}\left(\frac{1}{\langle\sigma_{ann}v\rangle}\right)$$

Turner-Scherrer

Putting in the numbers:

$$\begin{aligned}\langle\sigma_{ann}v\rangle &= 1 \ \ \mathrm{pb}\\ &= \frac{\pi\alpha^2}{8m^2}\end{aligned}$$

for m = 100 GeV

This strongly suggests:

- Dark matter is connected to electroweak symmetry breaking
- LHC will see the missing energy + multijets signature
- Underground experiments should probably see a cosmic dark matter signal

In this context, the LC will have an important role:

- determine the spin and EW quantum nos. of the N
- determine the parameters from which $<\sigma v>$ is computed

We would like to confront a microscopic calculation of the density of N with the measured cosmic density, both at the 1% level of precision.

There is physics in the comparison of the microscopic and cosmic estimates:

super-WIMP (gravitino) dark matter Feng et al.

$$\Omega_{DM} = \Omega_N \; (m_G / m_N)$$

late-decaying particles

add to the entropy, dilute Ω_{DM}

The story become analogous to that of primordial nucleosynthesis, now at

$$t \sim 10^{-8} \text{ sec.}$$

So far, this is a well-known story.

But, specifically for SUSY, there are new issues:

1980's:

$m_{\tilde{l}} \sim 20$ GeV $\quad\quad \Omega_N \sim 1$

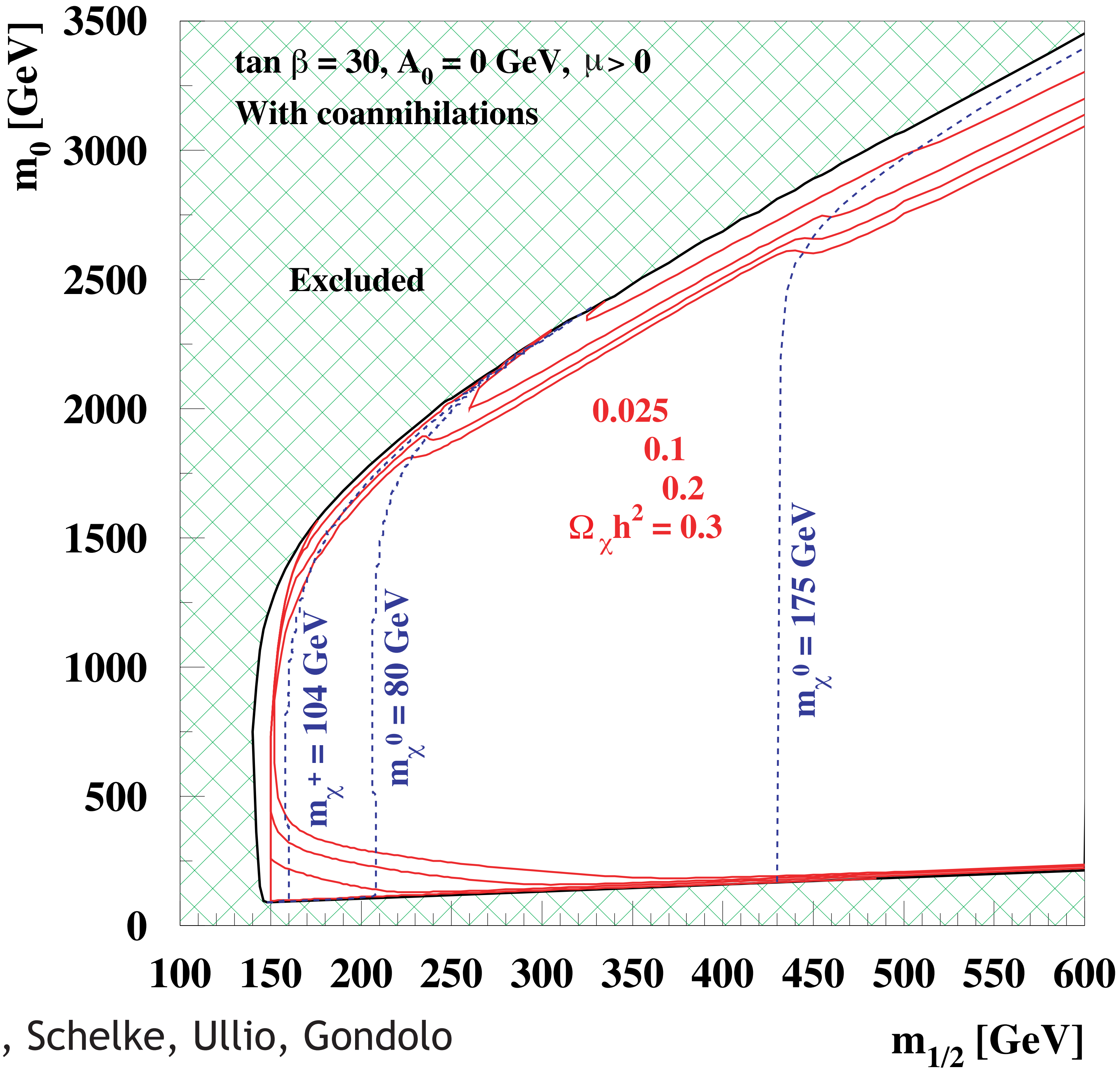
these are easily compatible using $N\, N \rightarrow l^+ l^-$

Today:

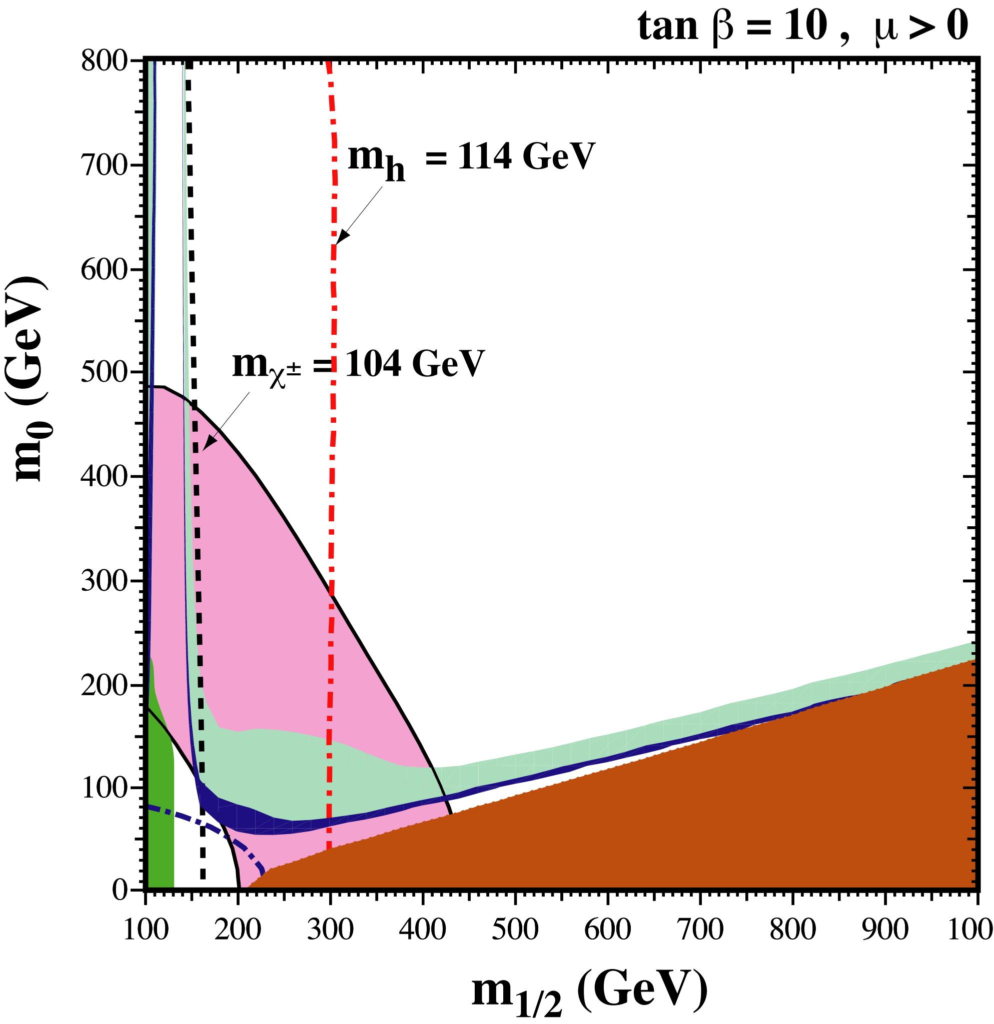
$m_{\tilde{l}} > 100$ GeV $\quad\quad \Omega_N \sim 0.2$

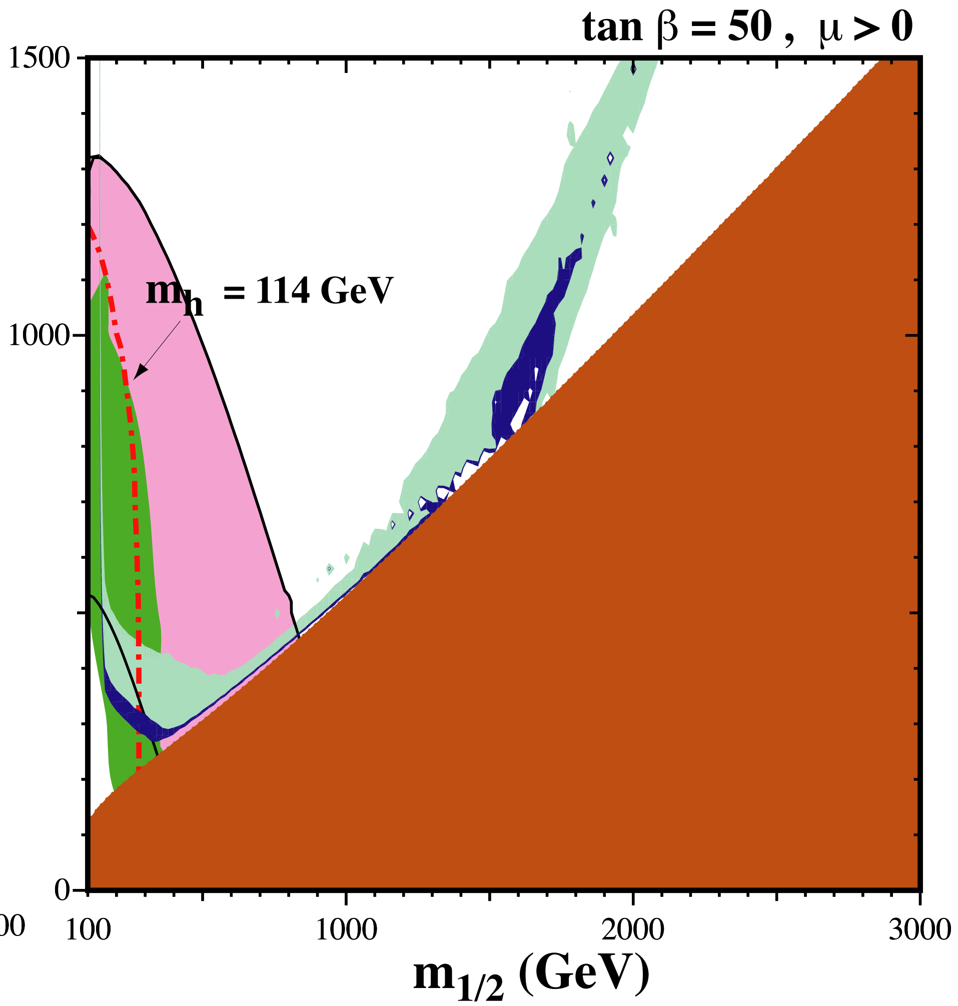
It doesn't work anymore!

Goldberg: $NN \rightarrow l^+ l^-$ goes in the P-wave, suppressing $\langle\sigma v\rangle$.



Edsjo, Schelke, Ullio, Gondolo





Ellis, Olive, Santoso, Spanos

For constrained minimal supergravity (`mSUGRA`), the region in which m_Z is naturally much less than 1 TeV is already almost excluded.

In the more general MSSM, natural regions are more robust,

but these still involve special features of the SUSY spectrum that allow $<\sigma v>$ for N annihilation to be atypically large.

$m(\tilde{l}) \sim m(N)$ slepton coannihilation region

large $<\sigma v>$ from $\tilde{l}\, N \rightarrow \gamma + l, \quad Z + l$

$m(\tilde{\tau}) \sim m(N)$ stau coannihilation region (large tan β)

large $<\sigma v>$ from $\tilde{\tau}\, N \rightarrow \gamma + \tau, \quad Z + \tau$

gaugino-Higgsino mixing in mSUGRA, focus point region

large $<\sigma v>$ from $N\,N \rightarrow W^+W^-$

$m(A) \sim 2\, m(N)$ A annihilation region

large $<\sigma v>$ from $N\,N \rightarrow A \rightarrow \ldots$

and also:

$m_1 \sim m_2$, stop coannihilation, ...

In each region, Ω_{DM} is extremely sensitive to some specific SUSY spectrum parameters:

slepton coannihilation

$n(\tilde{l})/n(N) \sim \exp(-\,x\ (m_{\tilde{l}} - m_N)/m_N\ )$

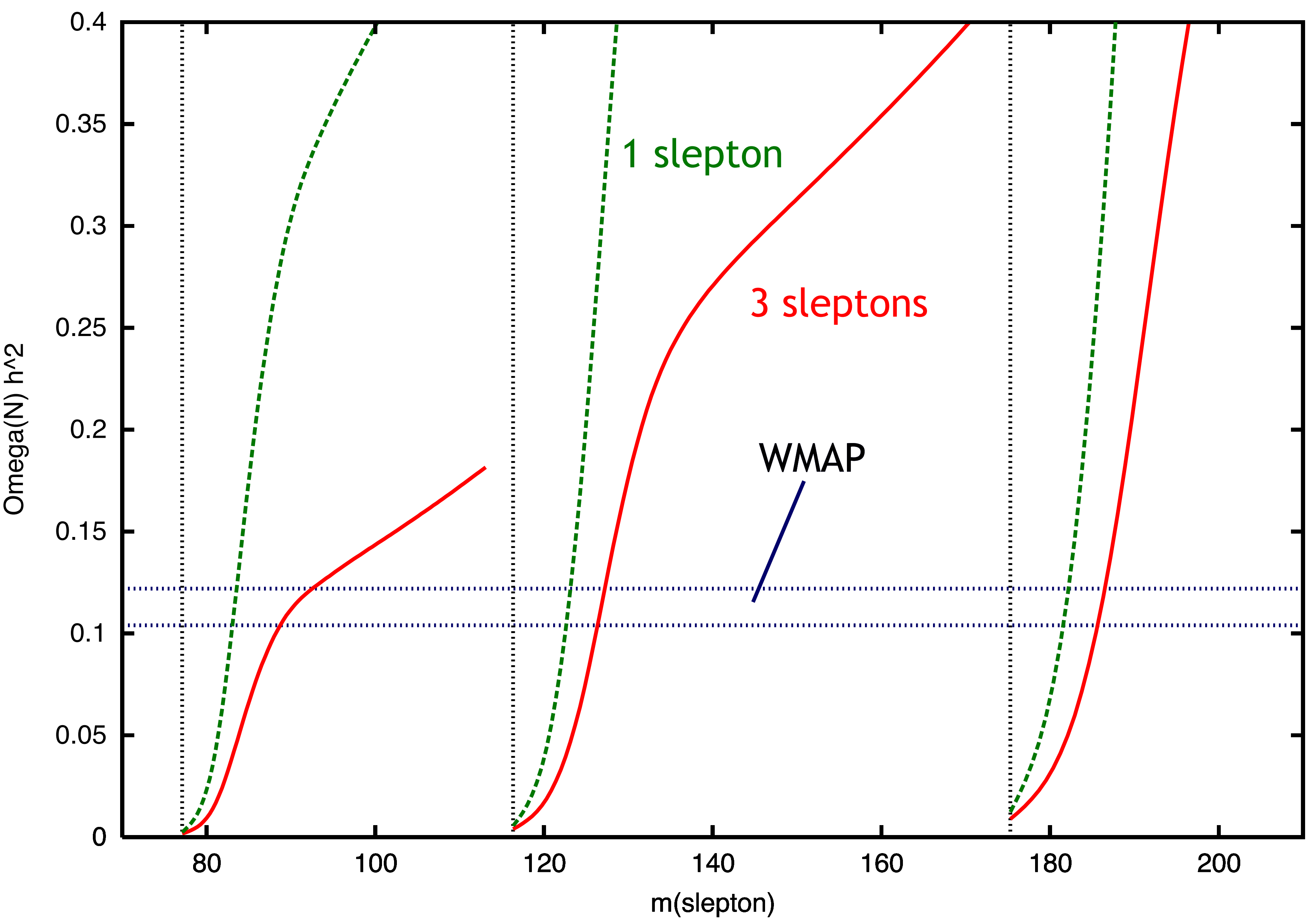
where $x = m_N/T \sim 20$ at freeze-out

gaugino-Higgsino mixing

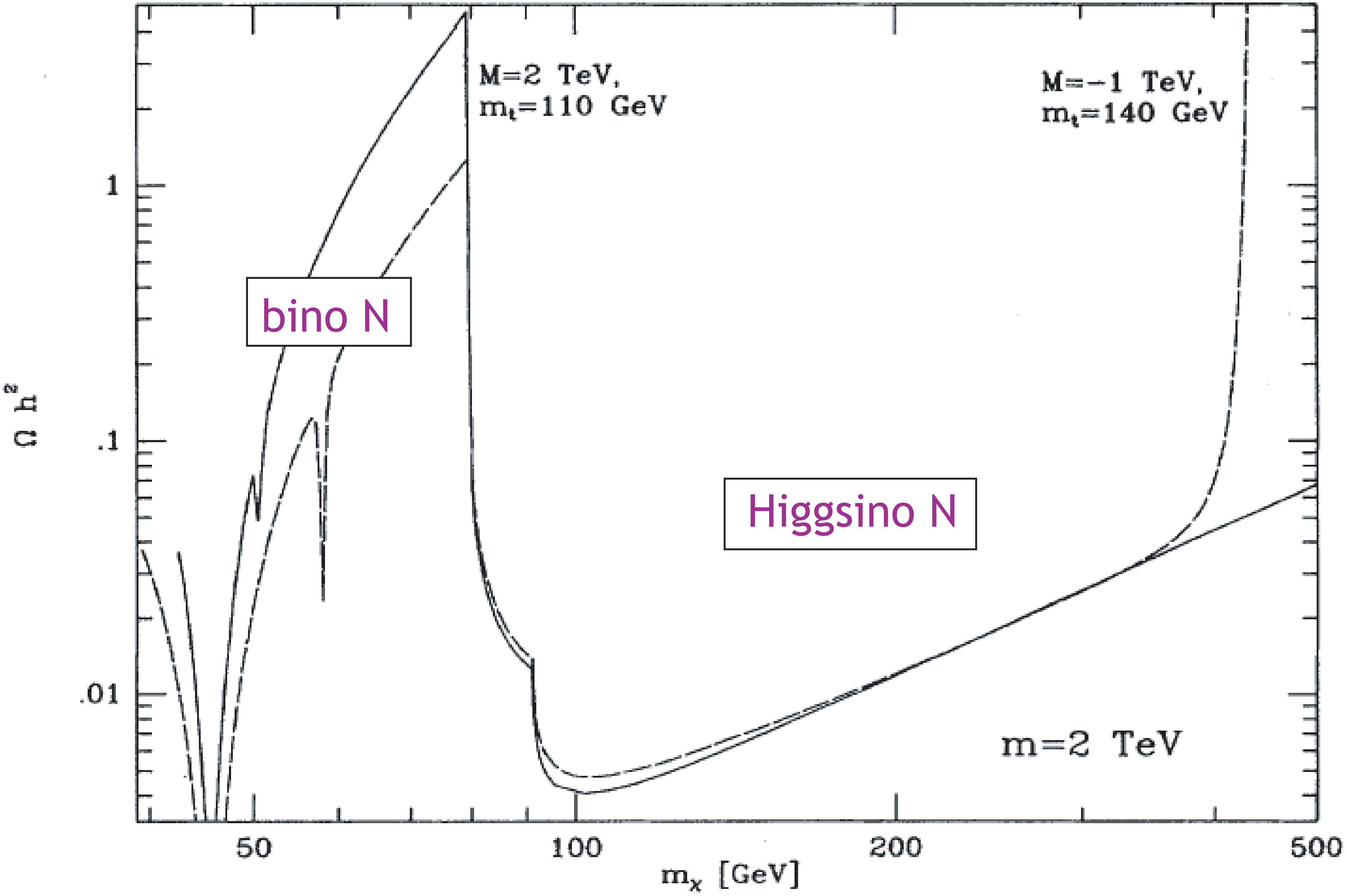
sharp transition as a function of mixing angle

A annihilation

strong dependence on $m(A) - 2\,m(N)$, $\tan\beta$


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

Yong and MEP



Drees and Nojiri

To understand these issues more quantitatively, a group of people in the US are choosing a set of study points for new physics simulations. We would like to evaluate

the experimental accuracy on parameters expected at LC

the theoretical sensitivity of Ω_{DM} to MSSM parameters

to assess whether the LC can indeed give a microscopic prediction of Ω_{DM} to 1% for comparison with Planck results.

For convenience in specification, choose mSUGRA points; however, we focus on the relation between Ω_{DM} and TeV-scale parameters determined by experiment.

Choose points for which some SUSY particles are observed at 500 GeV.

I personally believe that we will see SUSY at 500 GeV, but, in any event, analyses scale to higher SUSY masses and CM energies.

Relate to LHC studies where these exist,
in particular, studies at the Battaglia et al reference points

Unless otherwise stated (all masses in GeV)

$$\mathrm{sign}(\mu) = + \quad A_0 = 0 \quad m_t = 178$$

and reference theory from ISAJET 7.69 DarkSUSY

Current (preliminary) selection of points:

1: Bulk region / light sleptons

(use results from Desch et al on Snowmass 1a or Battaglia B')

$m_0 = 57$ $m_{1/2} = 250$ $\tan\beta = 10$ ISAJET 7.67

$m(N) = 95$ $m(\tilde{l}R) = 174$ $m(\tilde{\tau}R) = 167$ $m(C1) = 178$

2. Gaugino/Higgsino mixing focus point

Alexander, Matchev, and students

$m_0 = 3280$ $m_{1/2} = 300$ $\tan\beta = 10$ $m_t = 175$

$m(Ni) = (108, 166, 190, 294)$ $m(Ci) = (159, 286)$

(cf. Battaglia et al E' with $m_t = 171$)

3. Stau coannihilation

Dutta, Kamon

$m_0 = 213$ $m_{1/2} = 360$ $\tan\beta = 40$ ISAJET 7.63

$m(N) = 144$ $m(\tilde{\tau}R) = 153$

4. A annihilation

Battaglia and students

$m_0 = 340$ $m_{1/2} = 400$ $\tan\beta = 51$ ISAJET 7.67

$m(N) = 160$ $m(\tilde{\tau}R) = 187$ $m(A) = 419$

at 500 GeV, A is constrained by precision Higgs study
at 1 TeV, HA production is open

We are also studying one point with the spectrum required for electroweak baryogenesis.

5. Electroweak baryogenesis

Strube, Lu, Graf

$m_0 = 600 \quad m_{1/2} = 200 \quad A_0 = -1300 \quad \tan\beta = 30$

$m(N) = 81 \quad m(\tilde{t}1) = 156 \quad m(C1) = 162$

Theoretical support/criticism from (among others)

Baer, Baltz, Feng, Gondolo, Olive+Santoso, Birkedal+Matchev

Your participation is also invited!

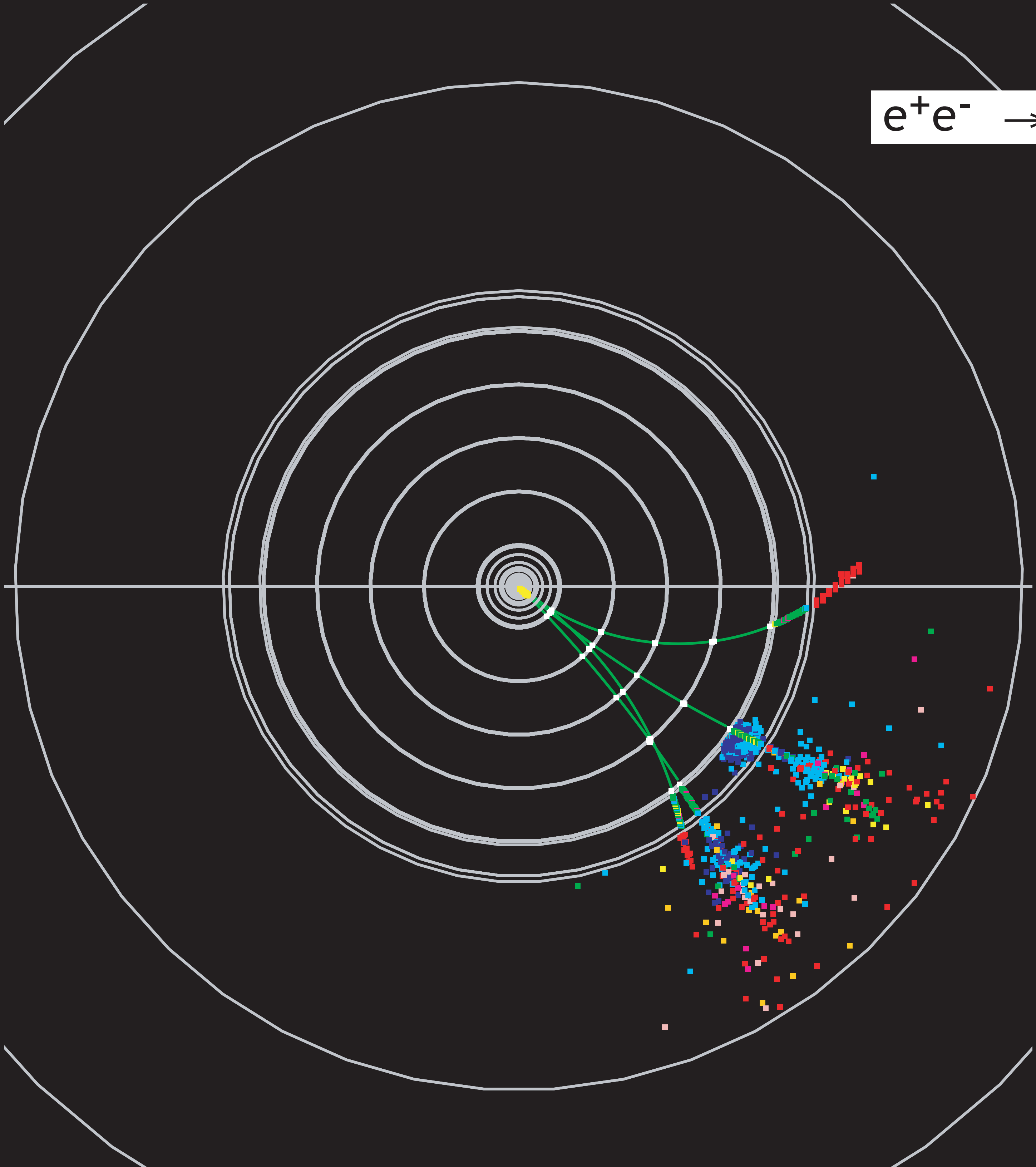
Studies are in progress. We expect results by the ALCPWG summer meeting in Victoria.

You should also look forward to a more general white paper on Linear Collider connections to cosmology, organized by Jonathan Feng and Mark Trodden. We would be happy to see contributions to both the studies and the document from the Asian and European regions.

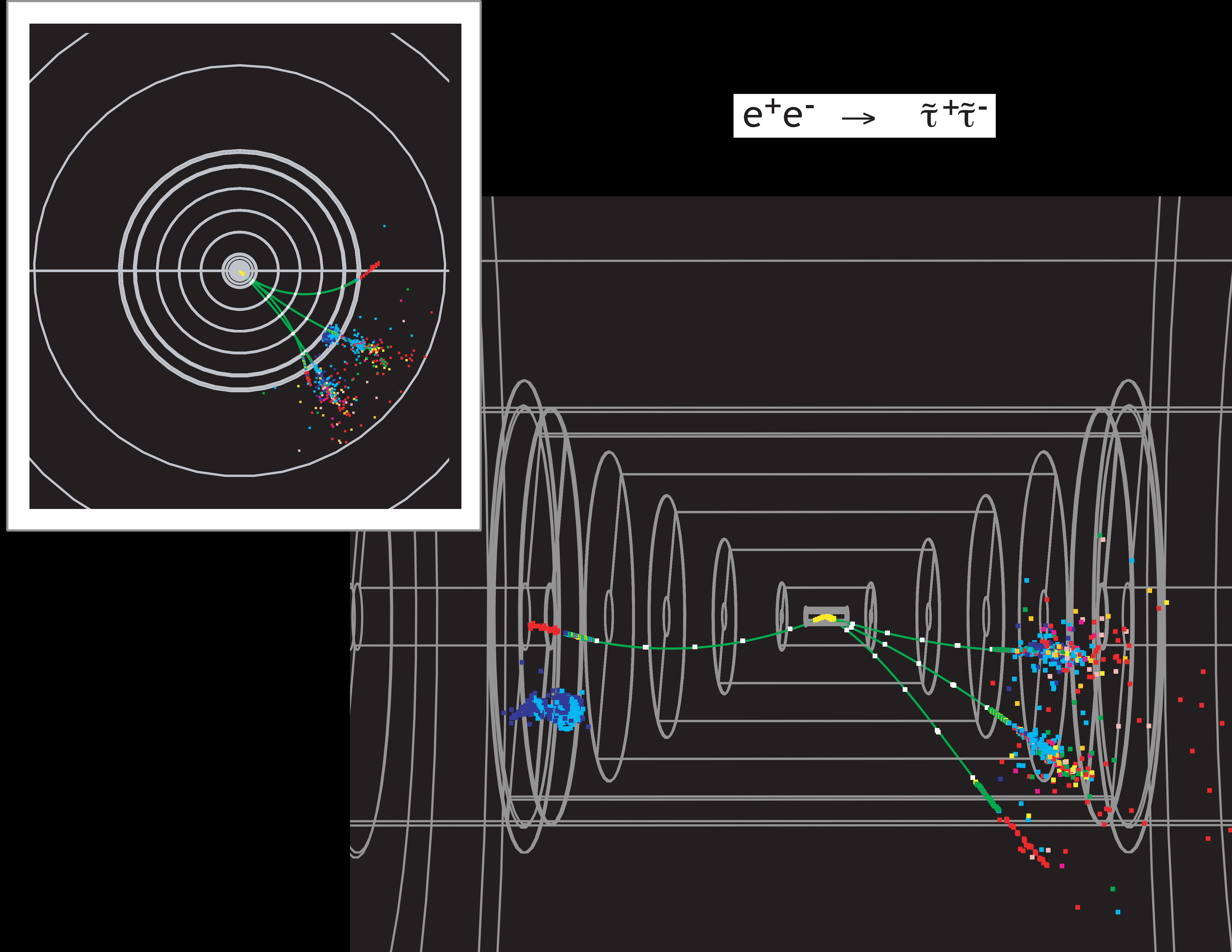
One final point:

I would like to illustrate what dark matter production should actually look like in the laboratory.

(thanks to Norman Graf)



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



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