Dark Matter and Colliders

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COSMO/CosPA, Tokyo, September 2010

Two Universes

Two Universes

shining Universe

Two Universes

shining Universe

Two Universes

shining Universe

dark Universe

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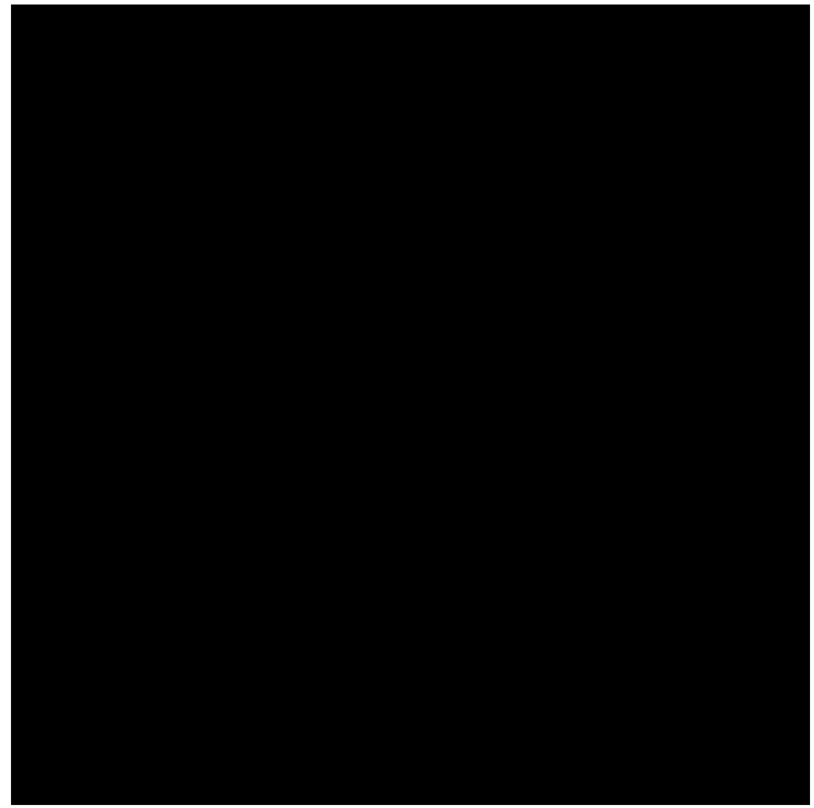
shining Universe

dark Universe



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- EWIMPs/superWIMPs and the LHC
- summary

The message:

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In revealing the nature of the dark matter in the Universe, the role of the LHC will not be just helpful, or complimentary.

It will be absolutely essential!

The case for dark matter

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- evidence for dark matter is convincing

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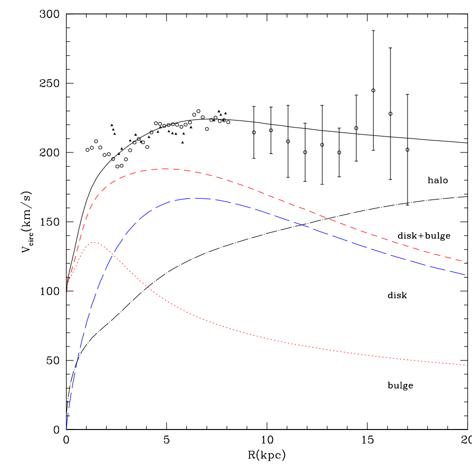
flat rotation curves



  - galactic scales (spirals, dwarfs, elliptical, ...)

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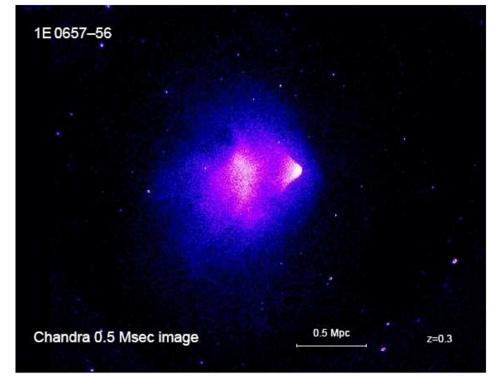
Bullet cluster, 2006



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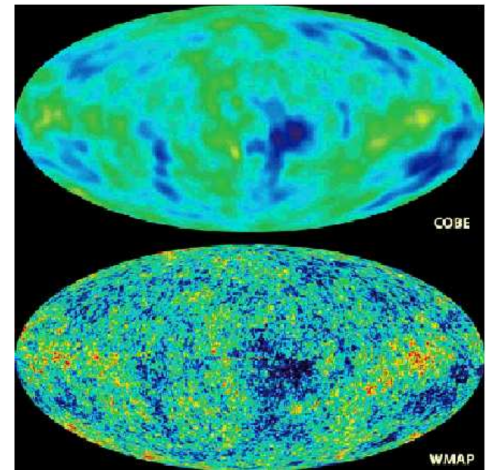
  - ...



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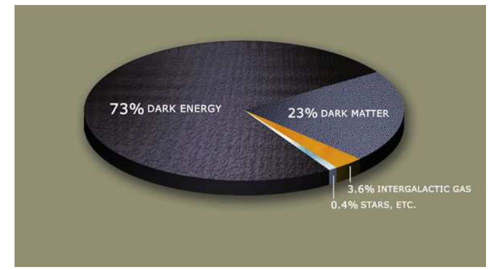

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$$\Omega_i = \rho_i / \rho_{crit}$$

- concordance ΛCDM model works well
- main components: dark energy and cold dark matter

$$\Rightarrow \boxed{\Omega_{\rm CDM} h^2 = 0.1152 \pm 0.0042}$$

- most natural candidate: WIMP

(weakly interacting massive particle)

WIMPs: thermal or (and?) non-thermal?

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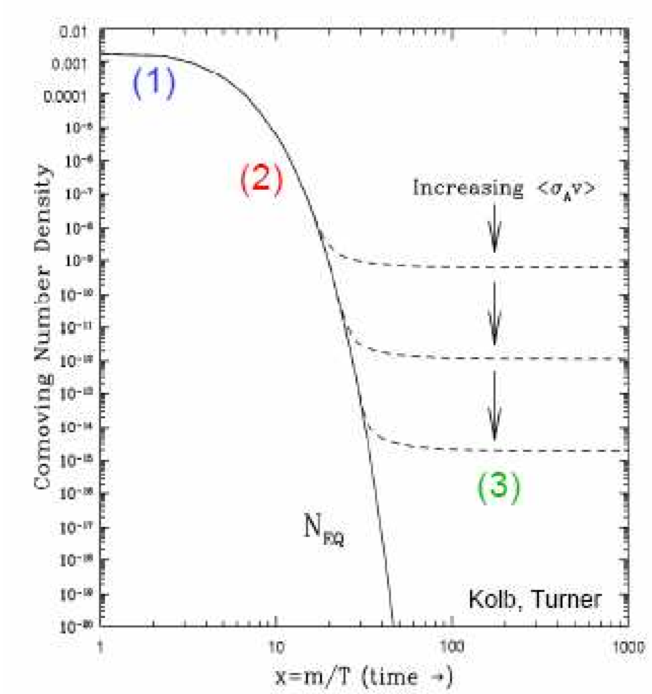
thermal

from freeze-out



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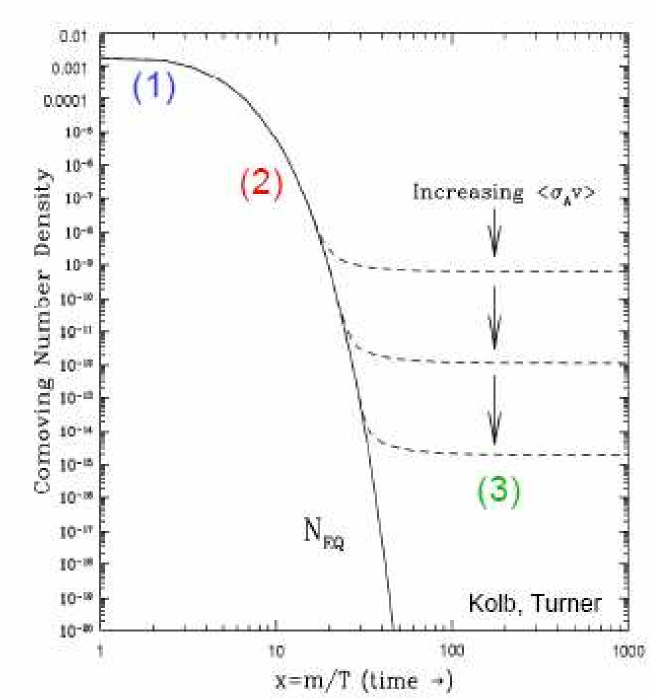
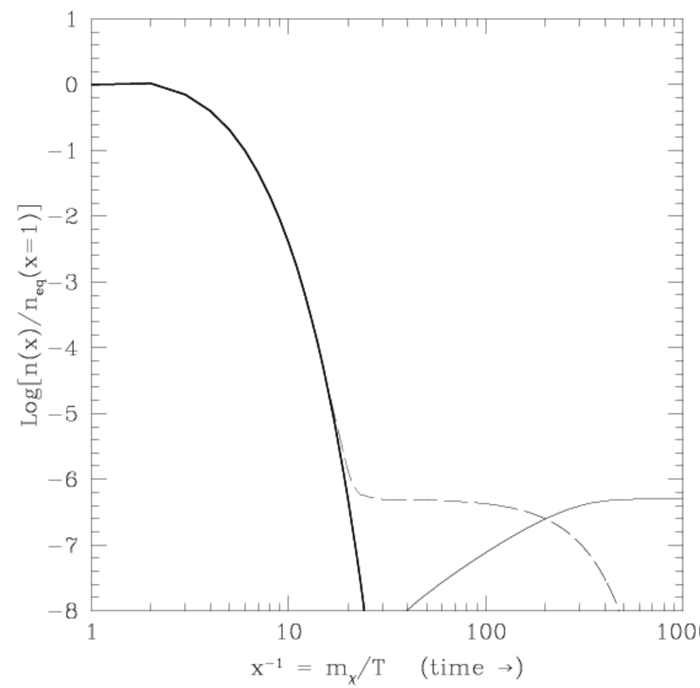


non-thermal

out-of-equilibrium, several mechanisms



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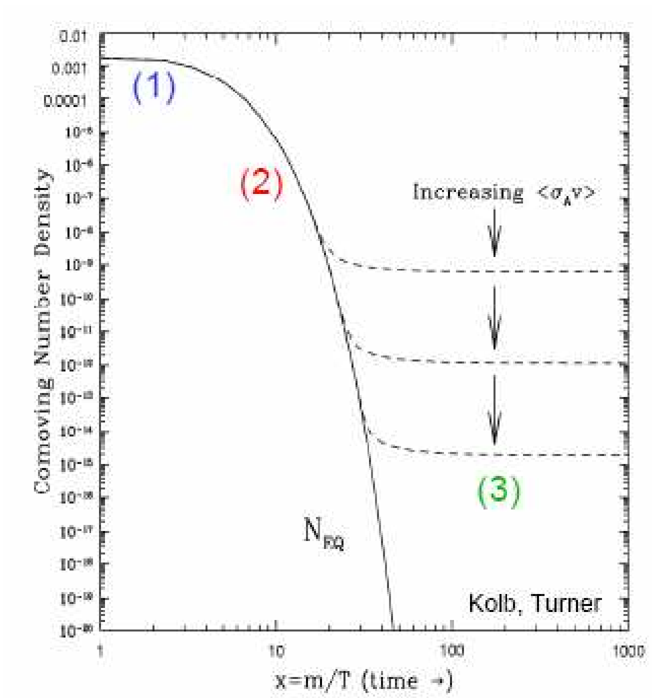

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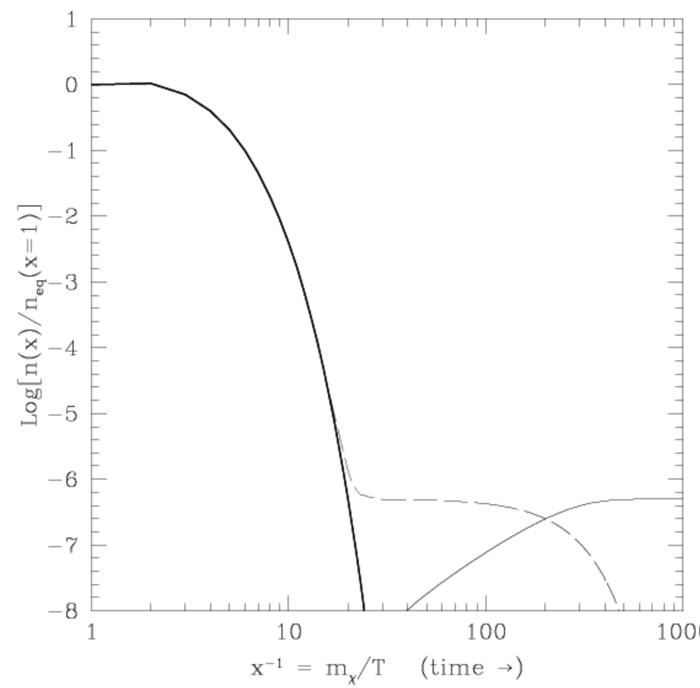

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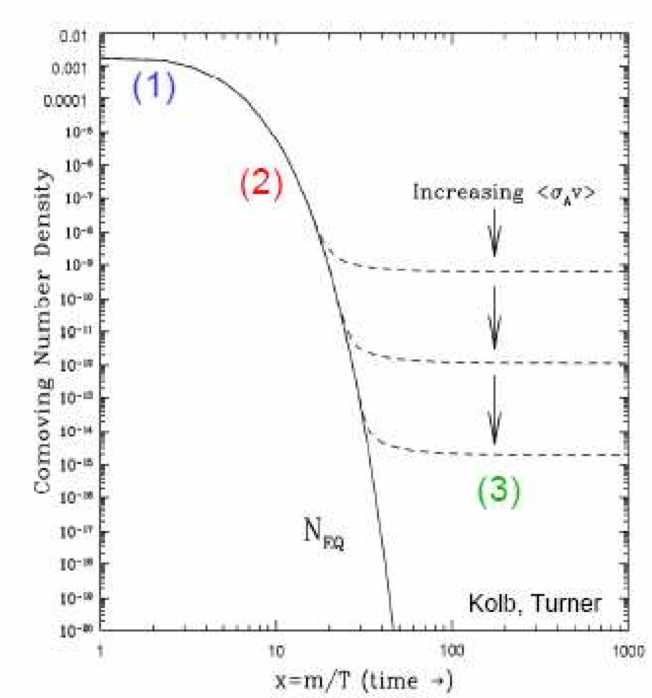

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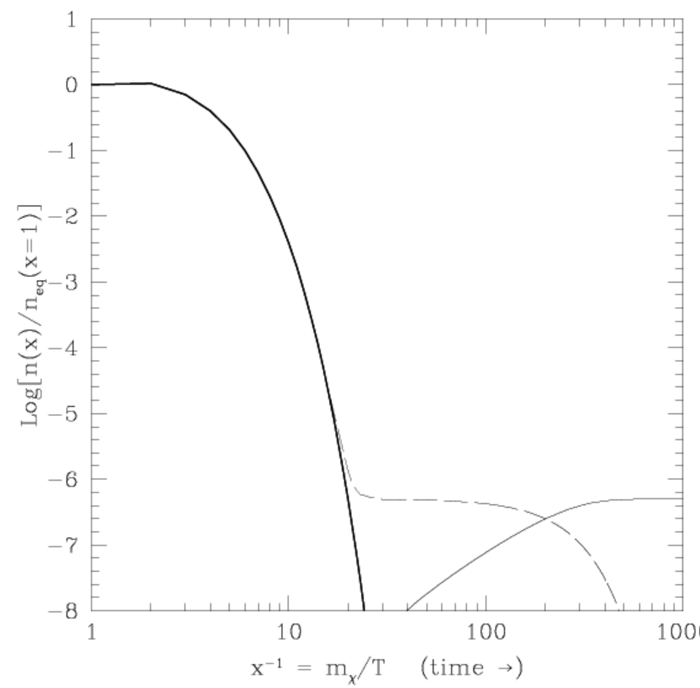


- thermal production (TP): robust, hard to suppress
- non-thermal production (NTP): more model-/mechanism- dependent, can be dominant, opens up new possibilities

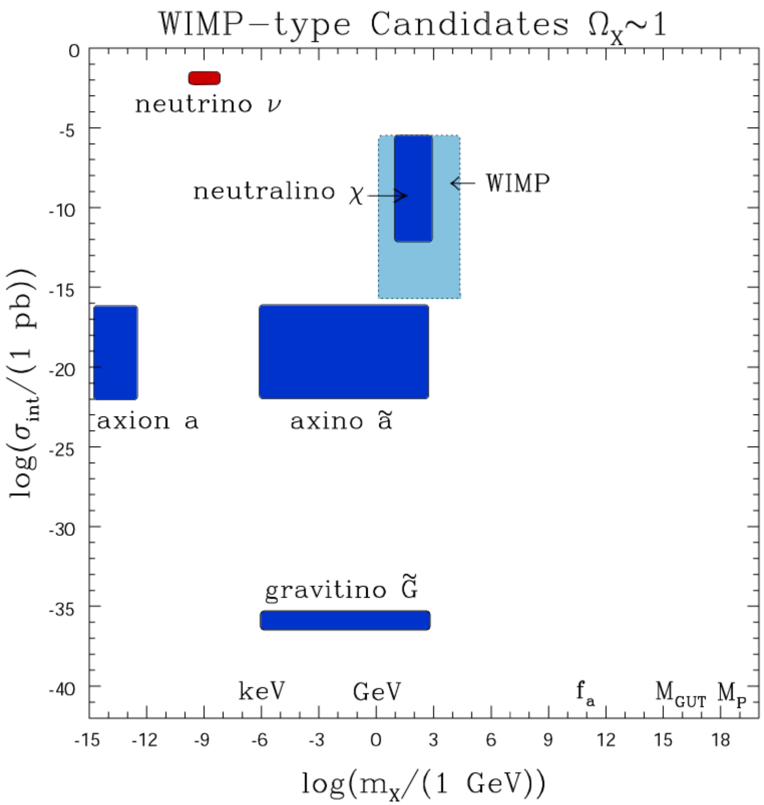
DM: The Big Picture

* – not invented to solve the DM problem

*well–motivated** particle candidates with $\mathbf{\Omega \sim 0.1}$

DM: The Big Picture

L.R. (2000), hep-ph/0404052



- neutrino ν – hot DM
- neutralino χ
- "generic" WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$

- vast ranges of interactions and masses
- different production mechanisms in the early Universe (thermal, non-thermal)
- need to go beyond the Standard Model
- WIMP candidates testable at present/near future
- axino, gravitino EWIMPs/superWIMPs not directly testable, but some hints from LHC

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No shortage of ideas... ...but few good ones, ...and even fewer longer-lasting

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several other interesting candidates: well-tempered neutralino, multiple (UPT) DM, little Higgs DM, mirror DM, shadow DM, sequestered DM, secluded DM, flaxino DM, Higgs portal DM, inflation and DM, modulus DM, etc etc. – no nonsense but not superior either

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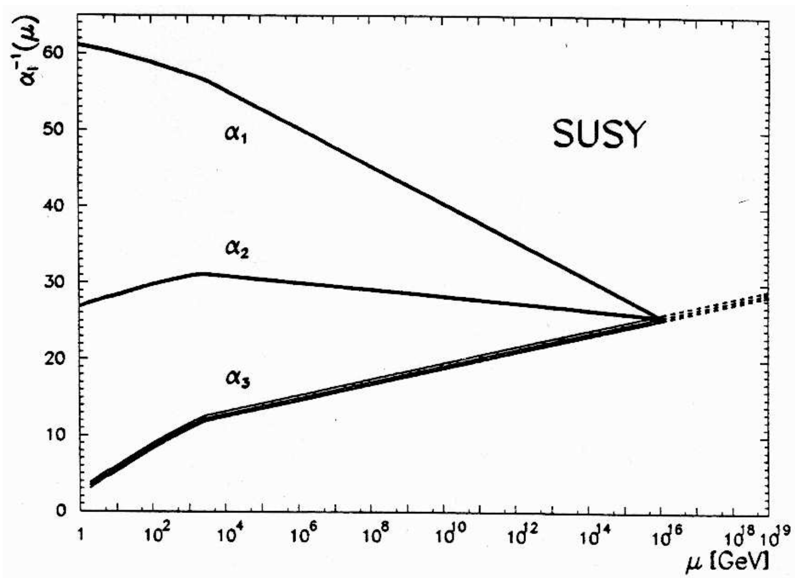
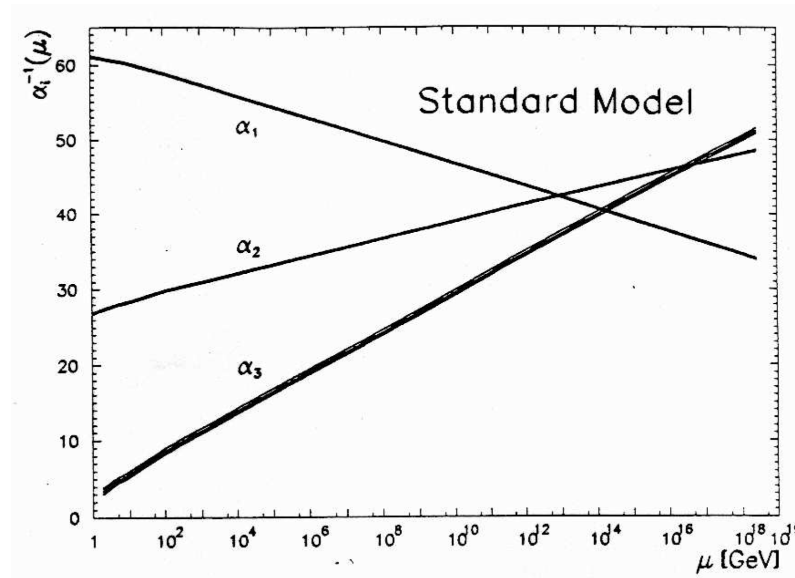
it is much (!) harder to invent a (lasting) model of 'new physics' containing a DM candidate

Supersymmetry

SUSY - by far the most popular and developed framework





gauge couplings “run” with energy

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neutralino $\chi =$ lightest mass eigenstate
of neutral gauginos $\widetilde{B}$ (bino), $\widetilde{W}_3^0$ (wino) and neutral higgsinos $\widetilde{H}_t^0$, $\widetilde{H}_b^0$
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- calculable
- relic density: $\Omega_\chi h^2 \sim 0.1$ from freeze-out (...more like $10^{-4} - 10^3$)
- stable with some discrete symmetry (e.g., R-parity or baryon parity)
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- multitude of SUSY-based models: general MSSM, CMSSM, split SUSY, MNMSSM, $SO(10)$ GUTs, string inspired models, etc, etc
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neutralino = stable, weakly interacting, massive $\Rightarrow$ WIMP

WIMP Detection

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Since the birth of time, mankind has searched everywhere for an answer to that age old question...

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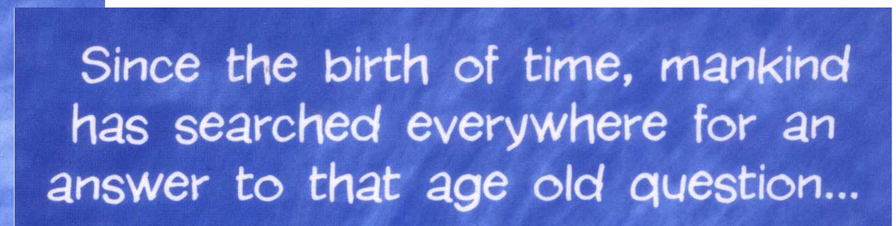

...go underground!

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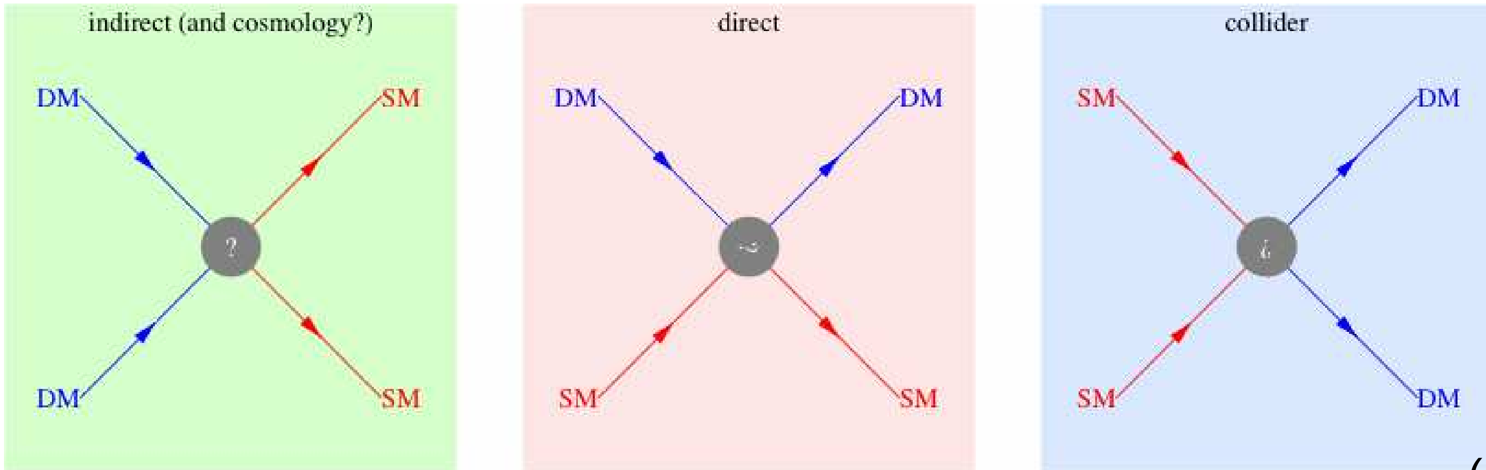
- colliders (the LHC)

Indirect, direct, collider



(Strumia)

but... usually NO crossing symmetry to help

reason: in each case different diagrams dominate

- ID: see talk by D. Murfatia
- DD: this and next talk
- colliders: this talk and talk by S. Asai

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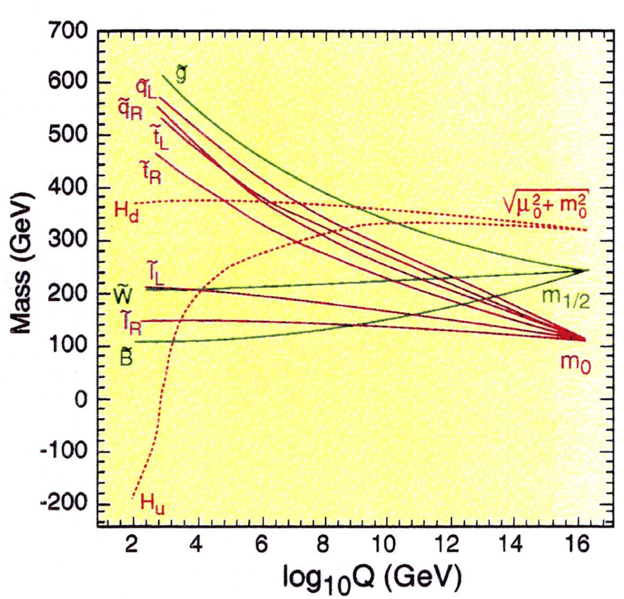
Kane, Kolda, LR, Wells (1993)

...“benchmark framework” for the LHC

(...e.g., mSUGRA)



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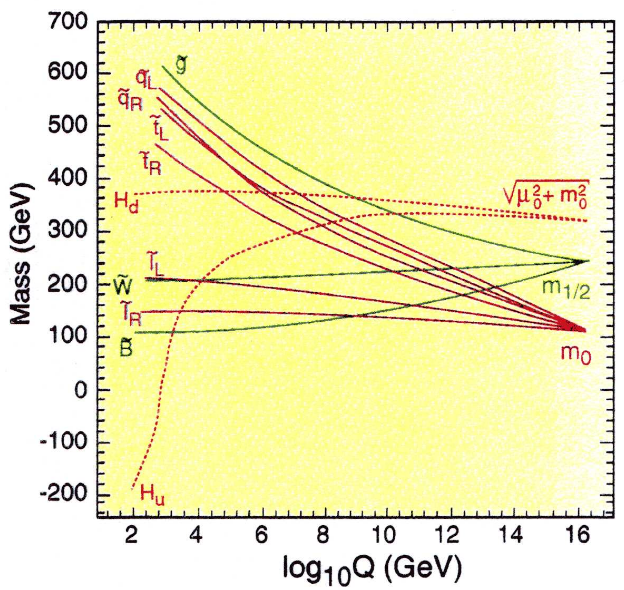

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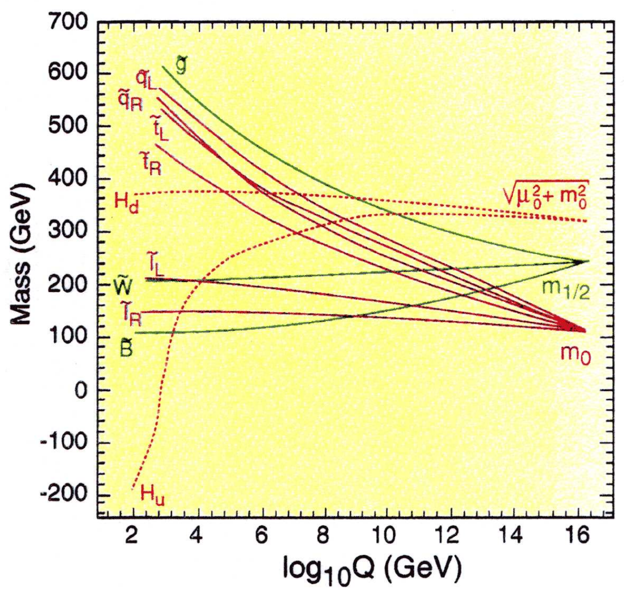

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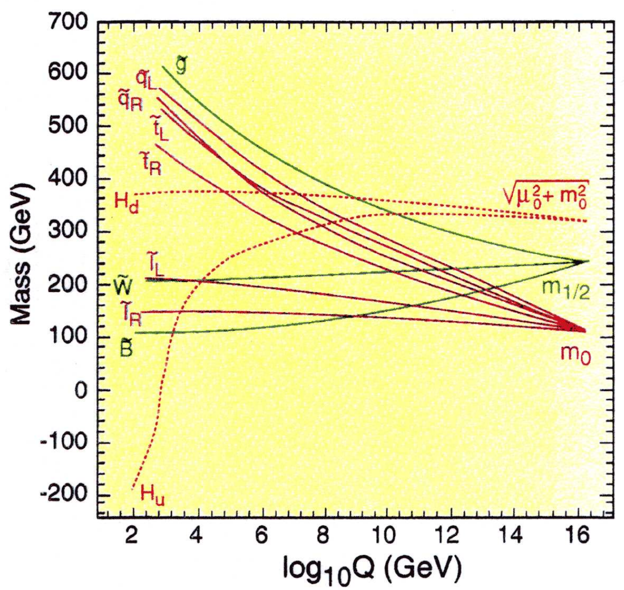

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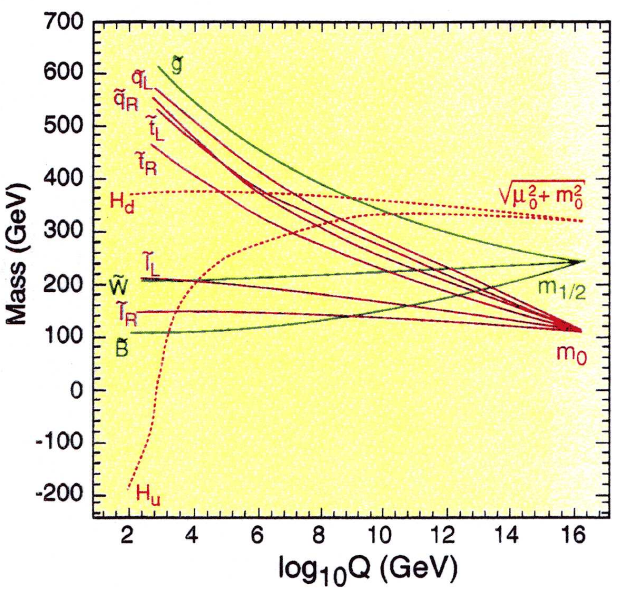

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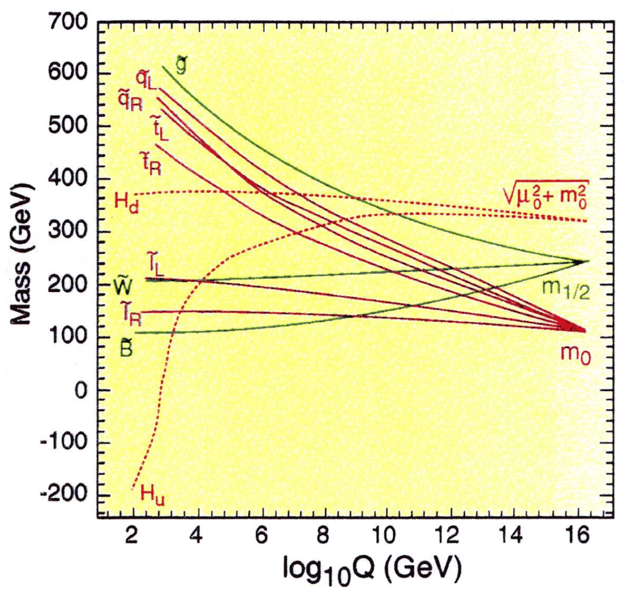

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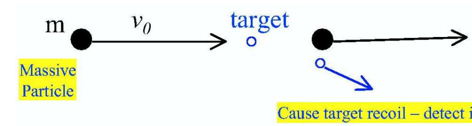
- well developed machinery to compute masses and couplings
- neutralino χ mostly bino

SUSY: Prospects for direct detection

Bayesian analysis, MCMC scan of 8 params (4 SUSY+4 SM)



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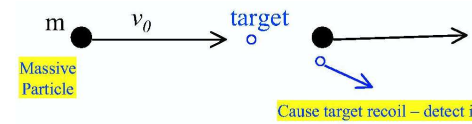

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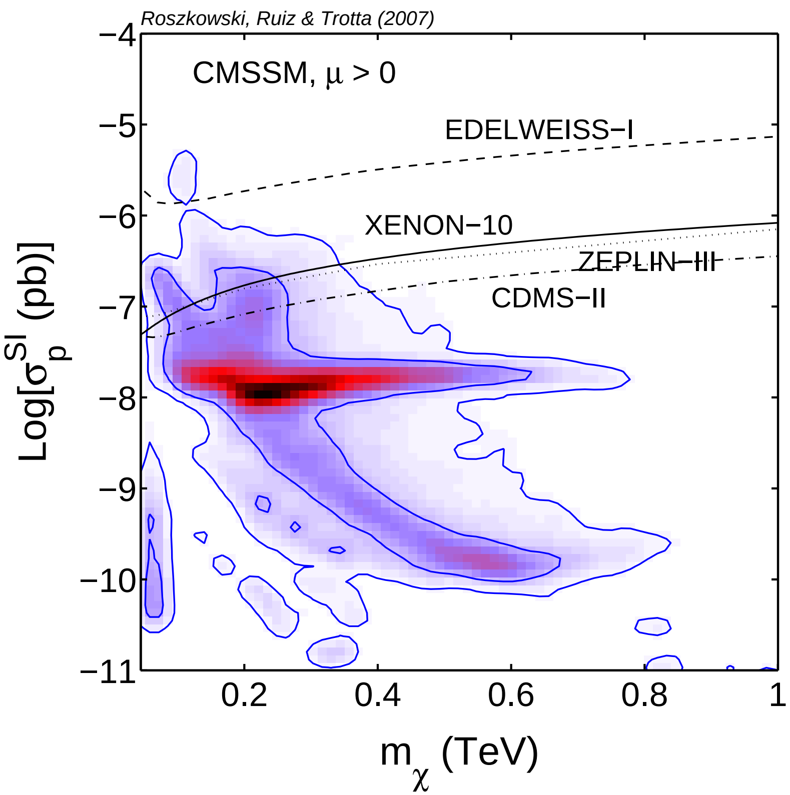

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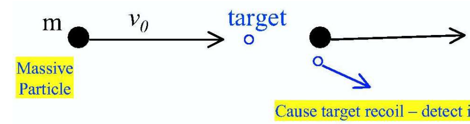

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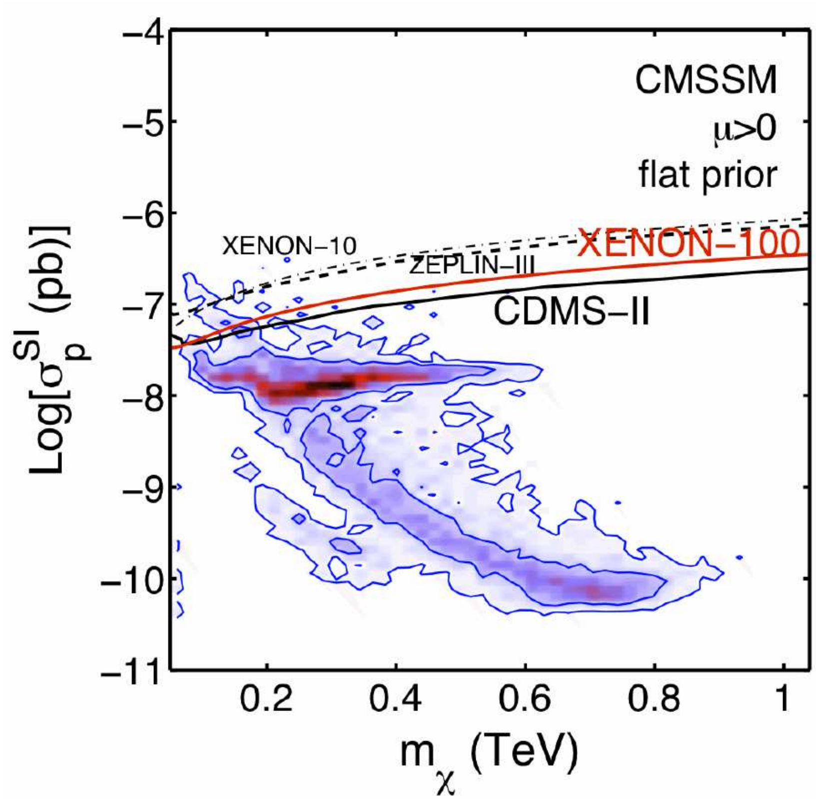

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currently best limits from:

XENON-100 and CDMS-II:

$\sigma_p^{SI} \lesssim 10^{-7}$ pb:

also Zeplin–III, Edelweiss

$\Rightarrow$ already explore most favored region

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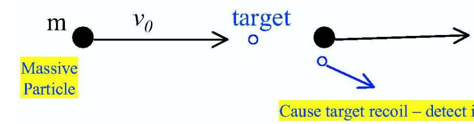

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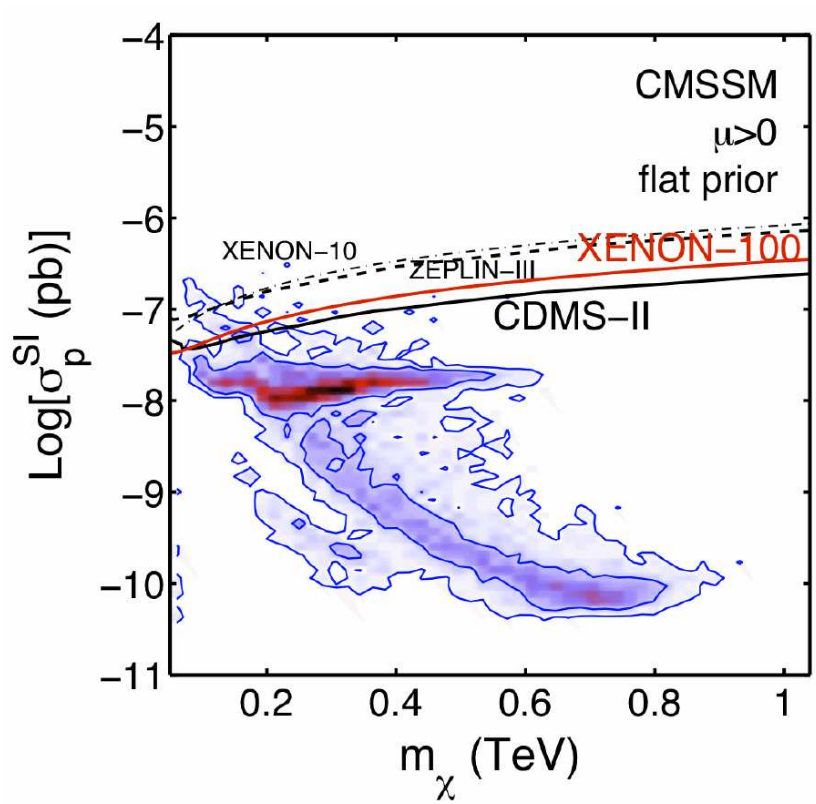

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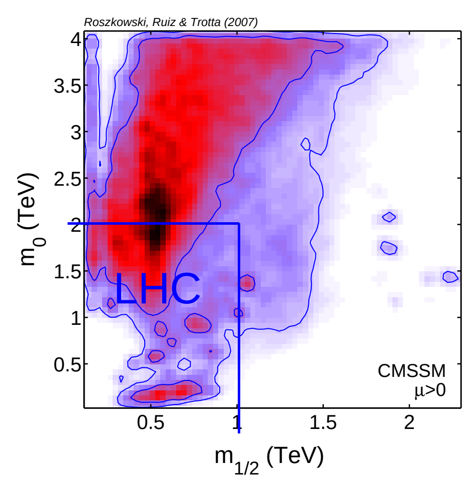

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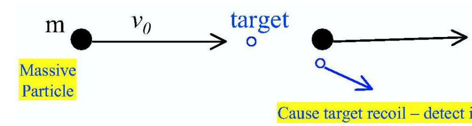

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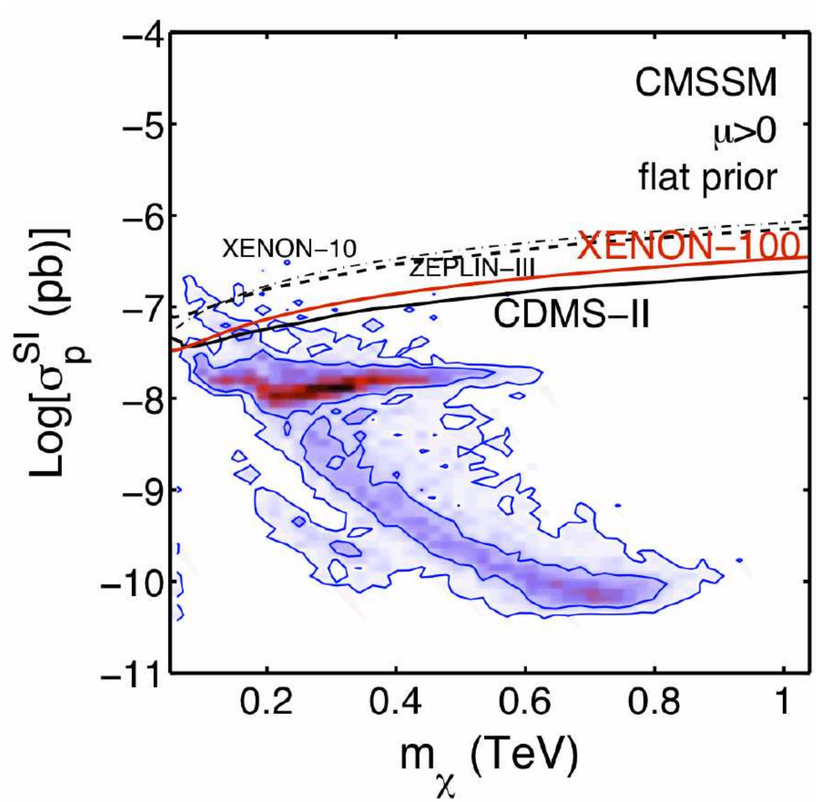

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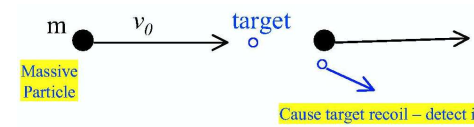
$\Rightarrow$ next: ZENON-100 - sensitivity reach $\sim 10^{-9}$ pb — later this year

$\Rightarrow$ future: 1 tonne detectors - sensitivity reach $\sim 10^{-10}$ pb — in a few years

SUSY: Prospects for direct detection



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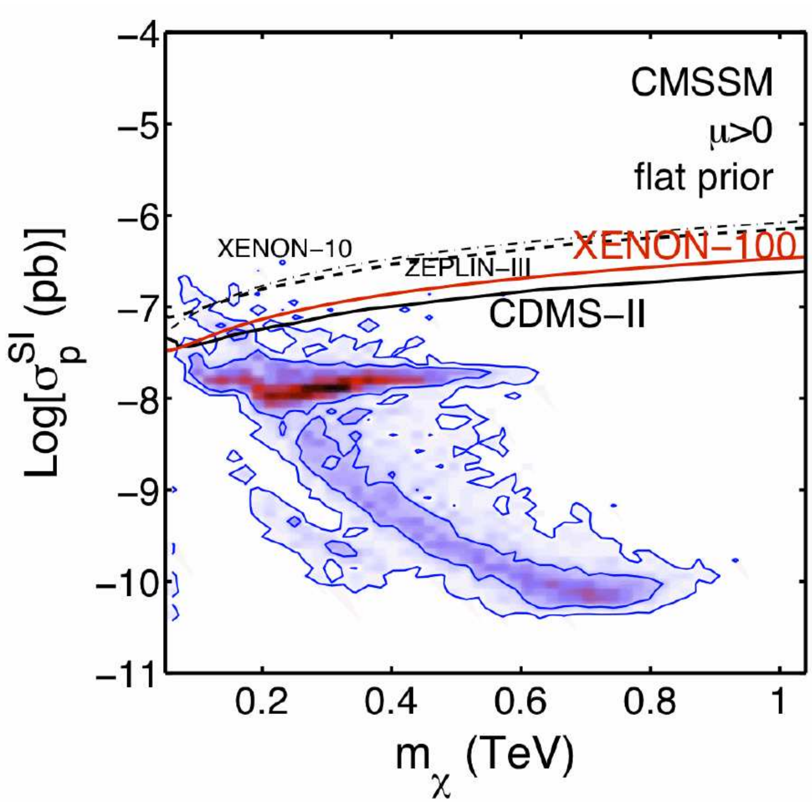

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$\Rightarrow$ direct detection: prospects look excellent

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Niels Bohr

Prediction is very difficult,

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especially if it's about the future.

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What shall we learn about the WIMP from direct detection?

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(...indirect detection: too many astrophysical uncertainties)

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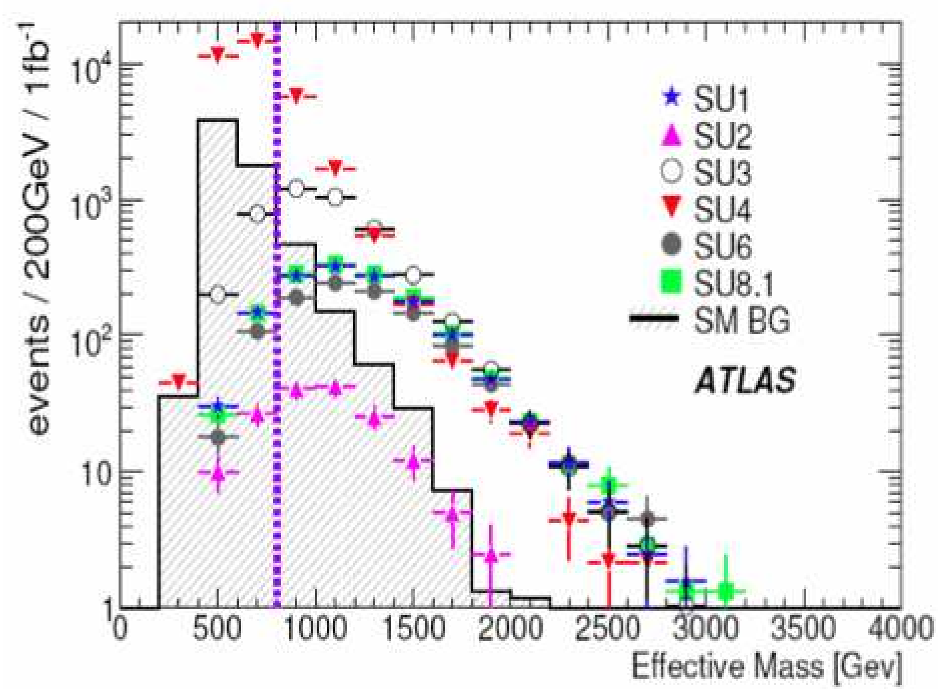

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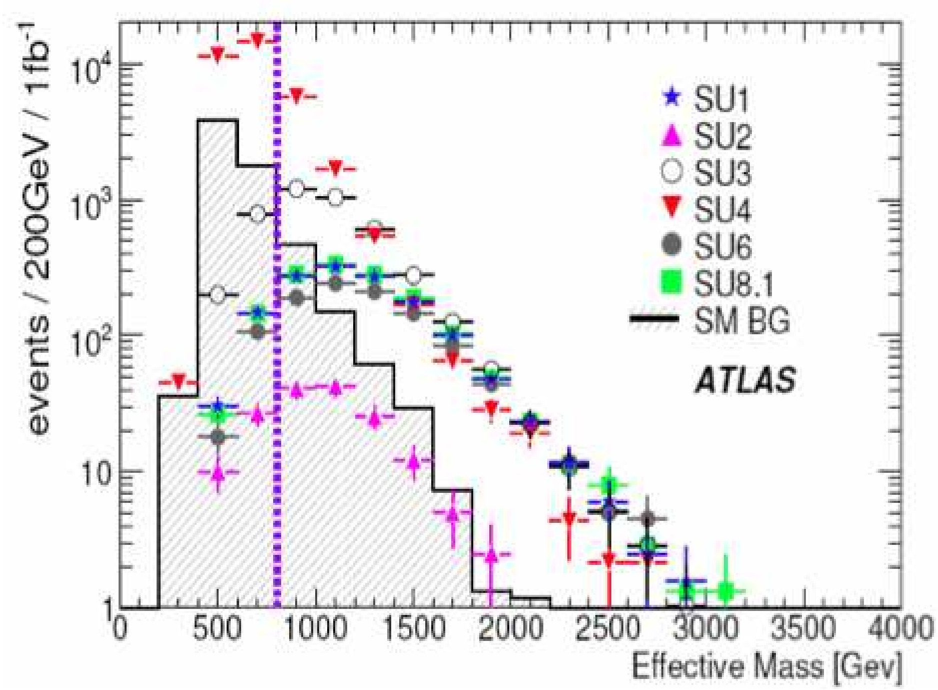

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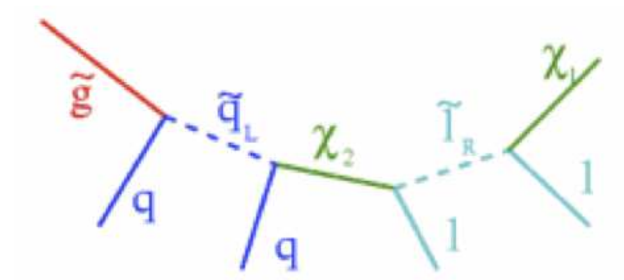

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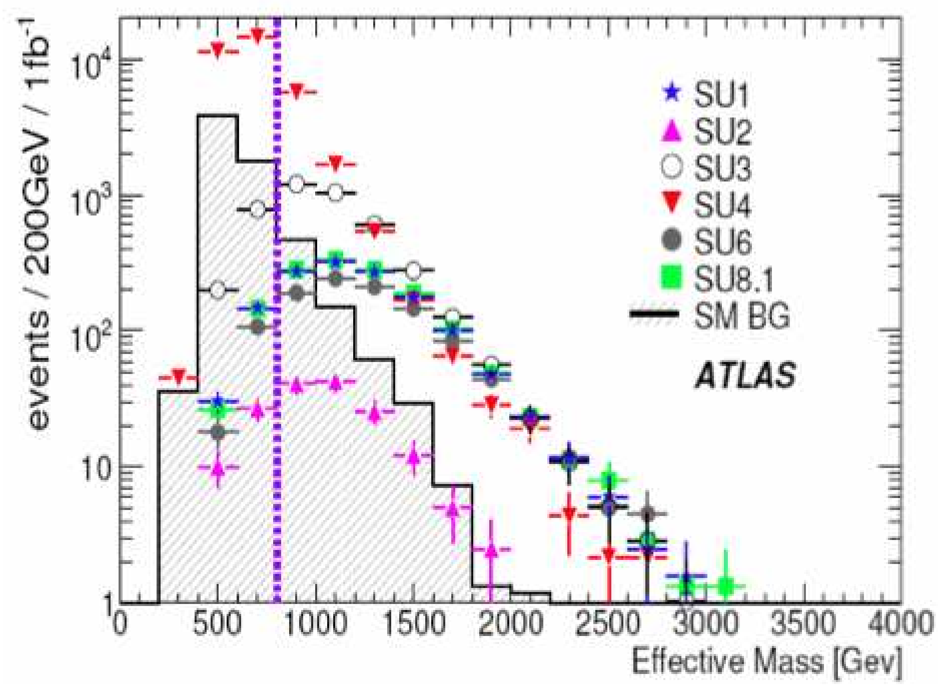

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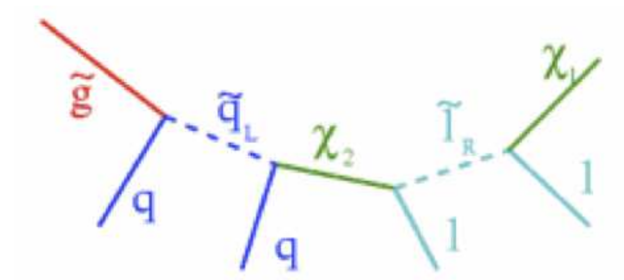

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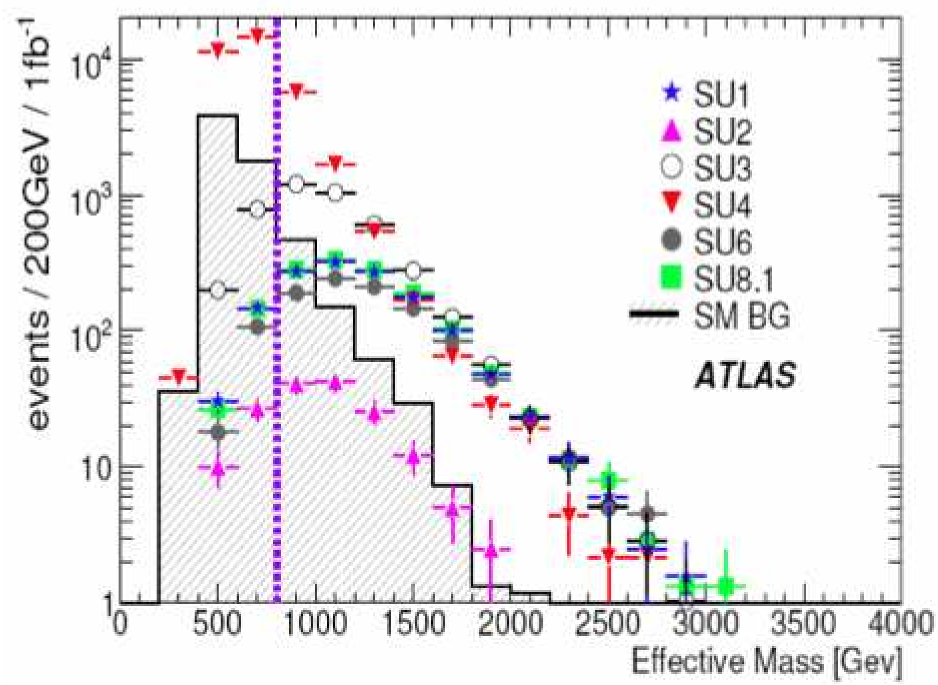

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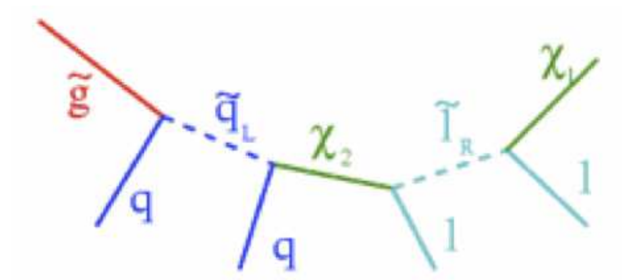

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$\Rightarrow$ Great triumph of the "standard paradigm"

— ...if SUSY indeed experimentally confirmed!

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Constrained MSSM (mSUGRA), ...huge volume of studies

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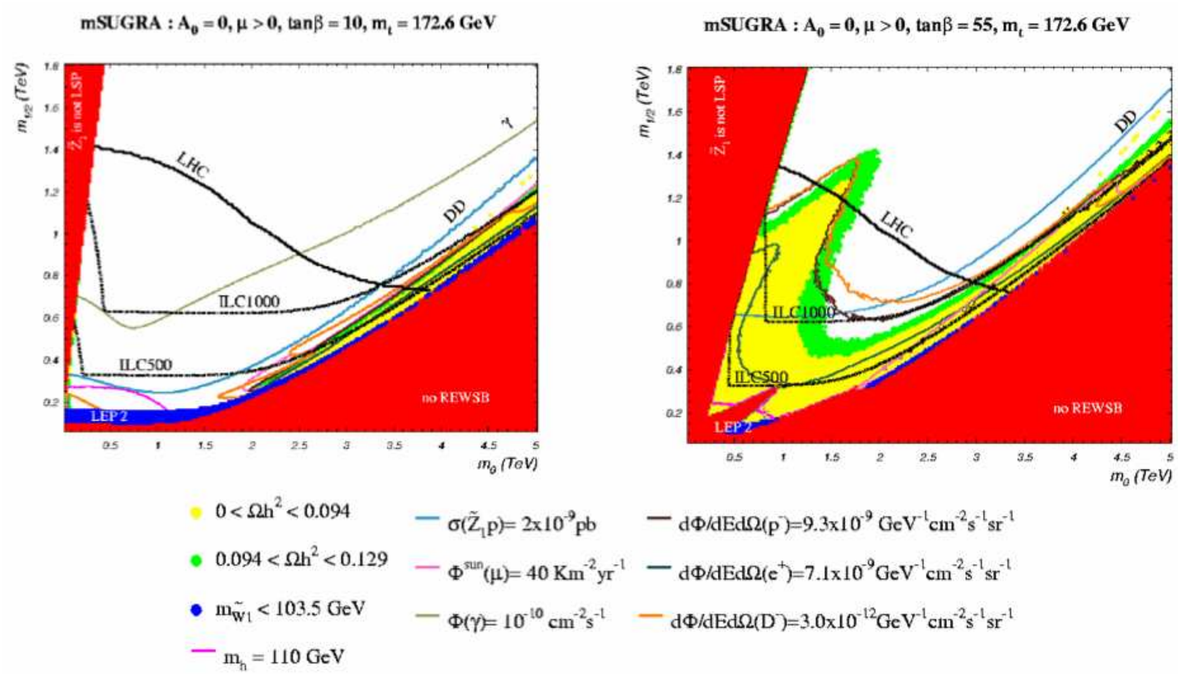

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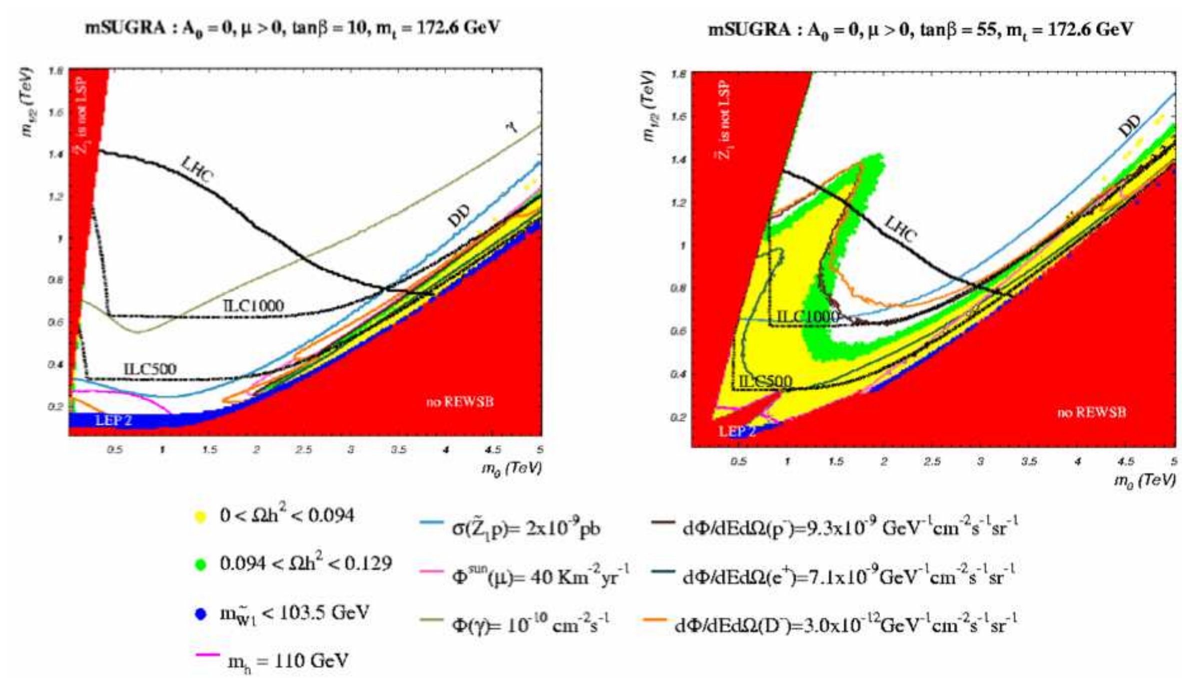

cosmologically favored (for fixed slices of CMSSM parameters):

- $\boldsymbol{A}$ funnel (AF)
- focus point (FP)
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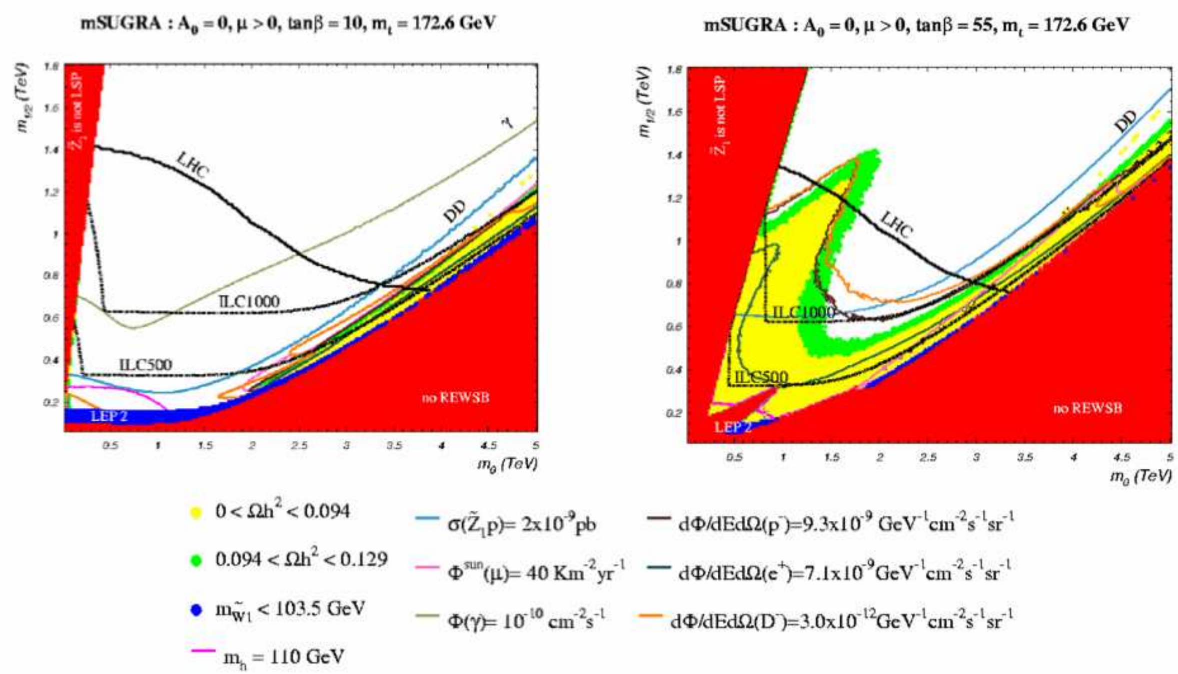

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- A funnel (AF)
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- DD: probe all FP and lower m_χ part of AF and CA
- LHC: probe lower m_χ part of AF and CA, poorer in FP
- ID strongly dependent on halo model

SUSY parameter reconstruction

Case study: ATLAS SU3 (CMSSM) benchmark point, arXiv:0901.0512

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Parameter	SU3 benchmark value
m_0	100 GeV
$m_{1/2}$	300 GeV
$\tan\beta$	6.0
A_0	-300 GeV
$\Omega_\chi h^2$	0.23319 $\Leftarrow$
SUSY mass spectrum	
$\chi = \chi_1^0$	117.9 GeV
χ_2^0	223.4 GeV
$\widetilde{m}_{\tilde{l}}$	152.2 GeV
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- $\widetilde{m}_{\tilde{l}}$ - lightest slepton mass
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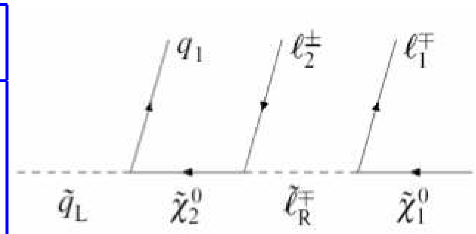

- study endpoint measurements
  - dileptons + lepton+jets analysis of the decay chain
    $\widetilde{q}_L \to \chi_2^0(\to \widetilde{l}^\pm l^\mp)q \to \chi_1^0 l^+ l^- q$
    and
  - the high-p_T and large missing energy analysis of the decay chain
    $\widetilde{q}_R \to \chi_1^0 q$
- χ^2 minimization
- int. lum. 1 fb^{-1}

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ATLAS SU3 benchmark point

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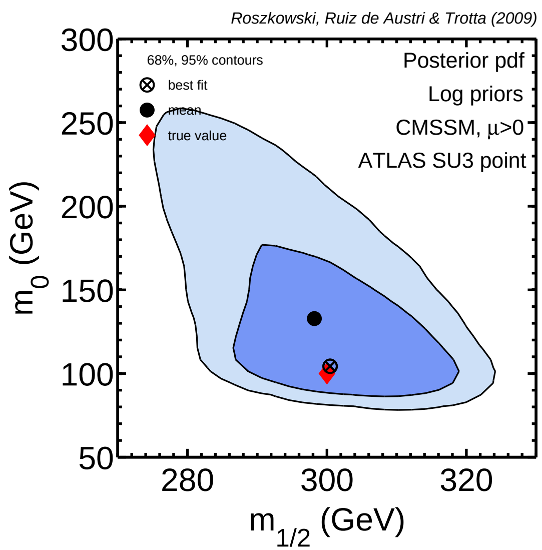

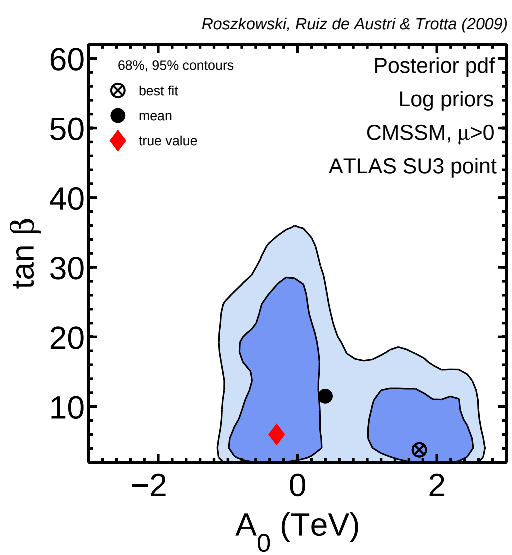

- red diamond: SU3 point
- green cross in circle: best-fit value
- big dot: posterior mean
- dark blue: 68% total prob. region
- light blue: 95% total prob. region

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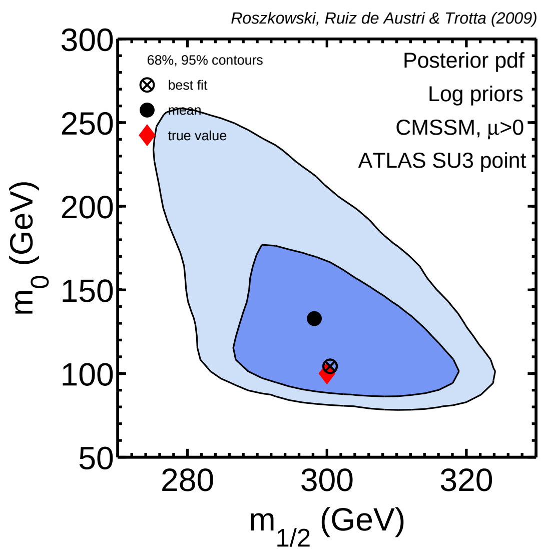
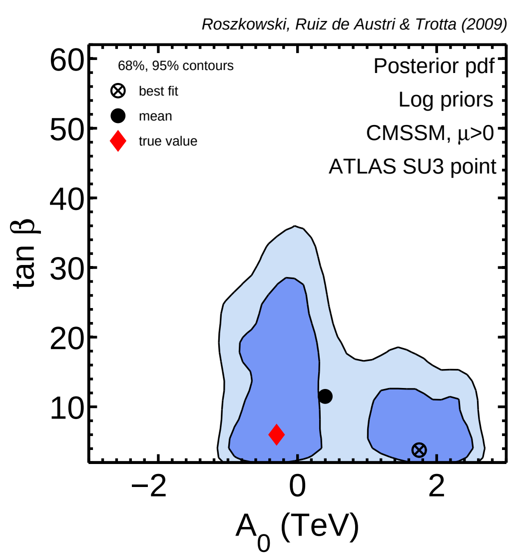


$\Rightarrow$ parameters reconstructed with reasonably good accuracy



Determining Neutralino's $\Omega_\chi h^2$ at LHC

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assume neutralino is the LSP

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  need to measure m_χ, Higgs, gluino and lightest squark masses, several BRs and $\tan\beta$ (depending on SUSY framework):

Nojiri, Polesello, Tovey ’04, SPA point

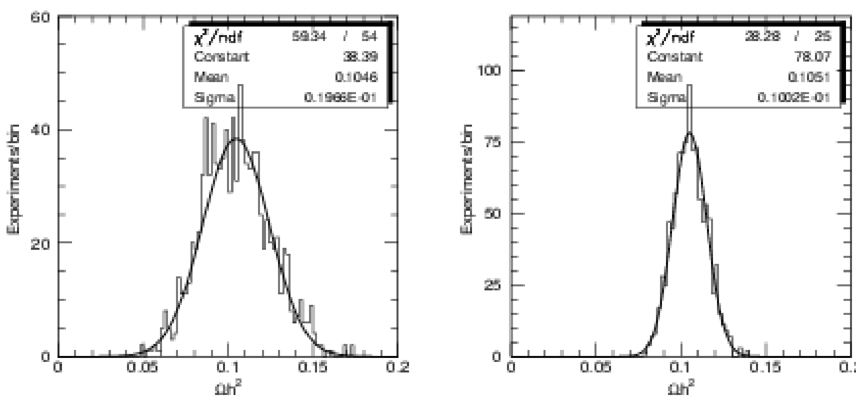
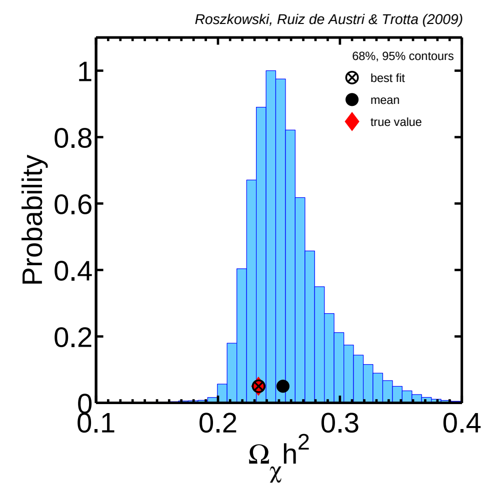


Figure 7: *Distributions of the predicted relic density $\Omega_\chi h^2$ incorporating the experimental errors. The distributions are shown for an assumed error on the $\tau\tau$ edge respectively of 5 GeV (left) and 0.5 GeV (right).*

ATLAS SU3 point



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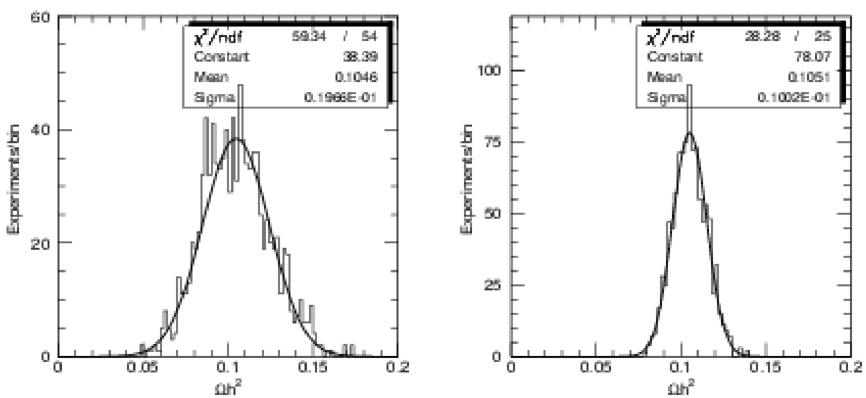

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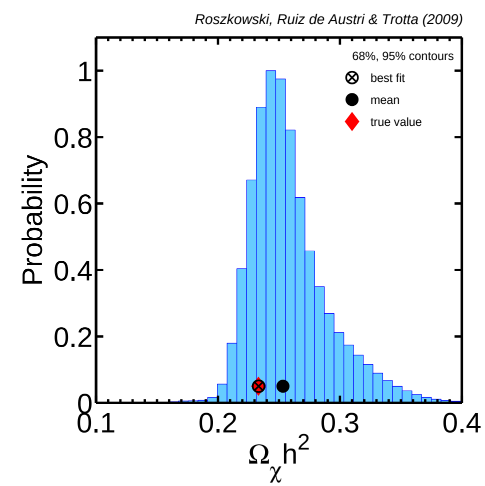

$\Rightarrow$ $\Omega_\chi h^2$ determination: $\sim$10% error achievable

Determining $\sigma_p^{\rm SI}$

assume Planck-like error: reduce WMAP error on $\Omega_\chi h^2$ by ~ 5 ($\lesssim 0.0016$)

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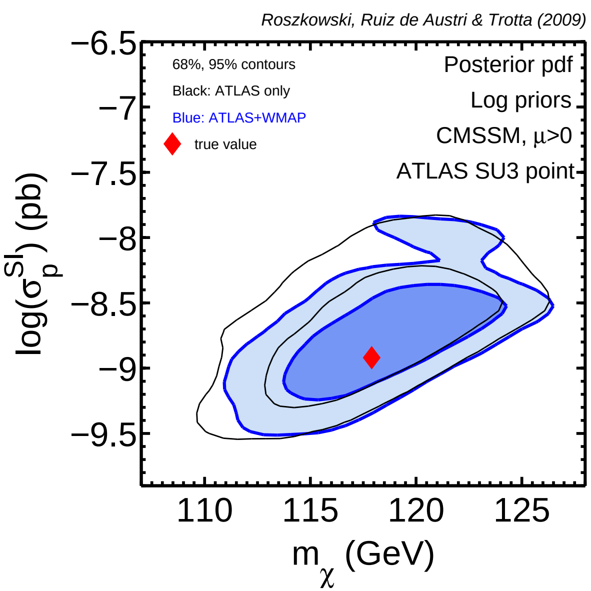

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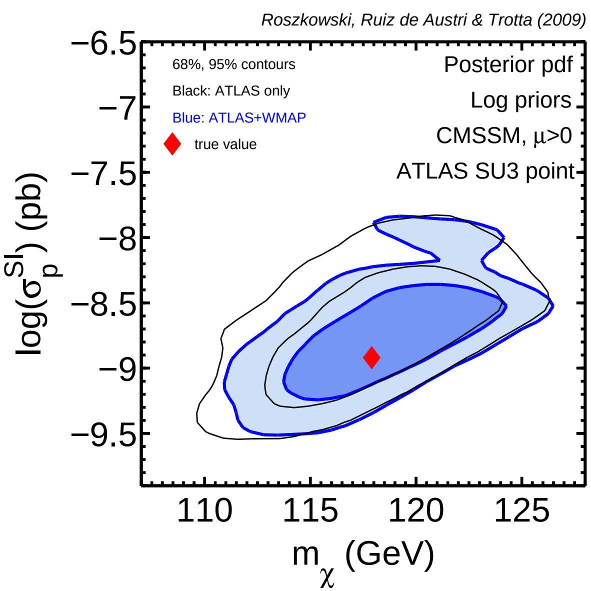

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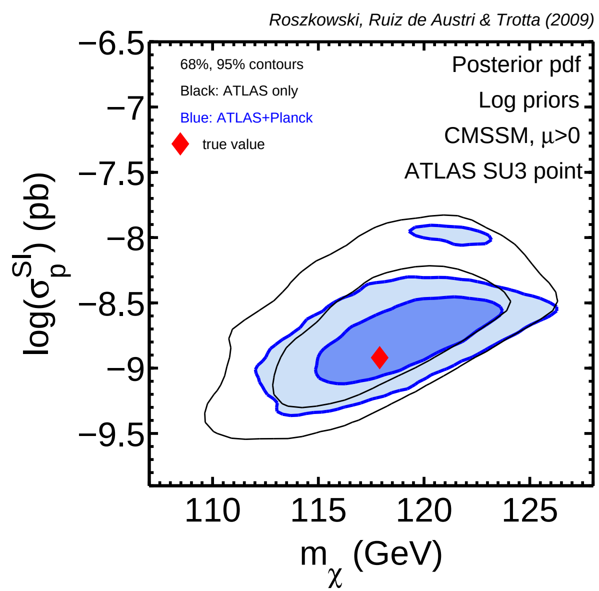

similar result for flat prior and profile likelihood

$\Rightarrow$ σ_p^{SI} determination reasonably good

SUSY models and DM direct detection

Bayesian analysis, flat priors

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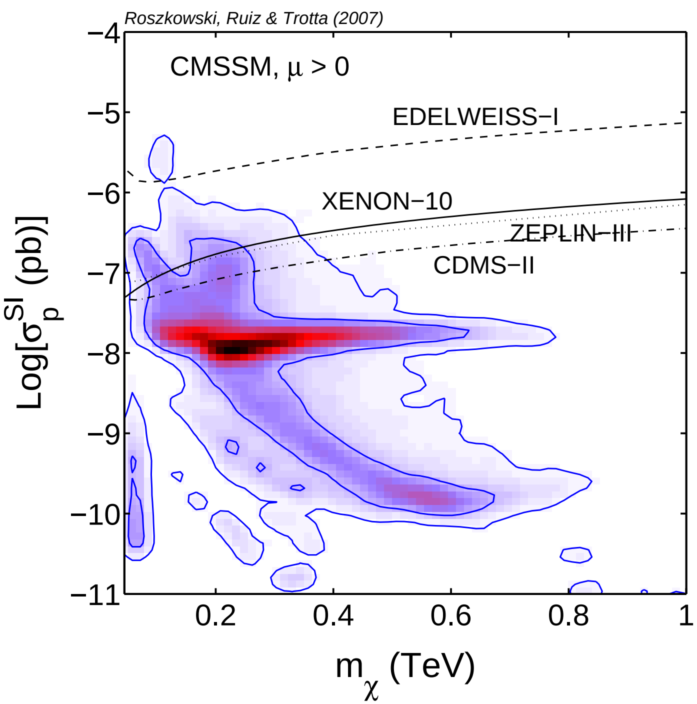
Constrained MSSM (mSUGRA)



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Higgs: H_u, H_d and singlet S; λS^3

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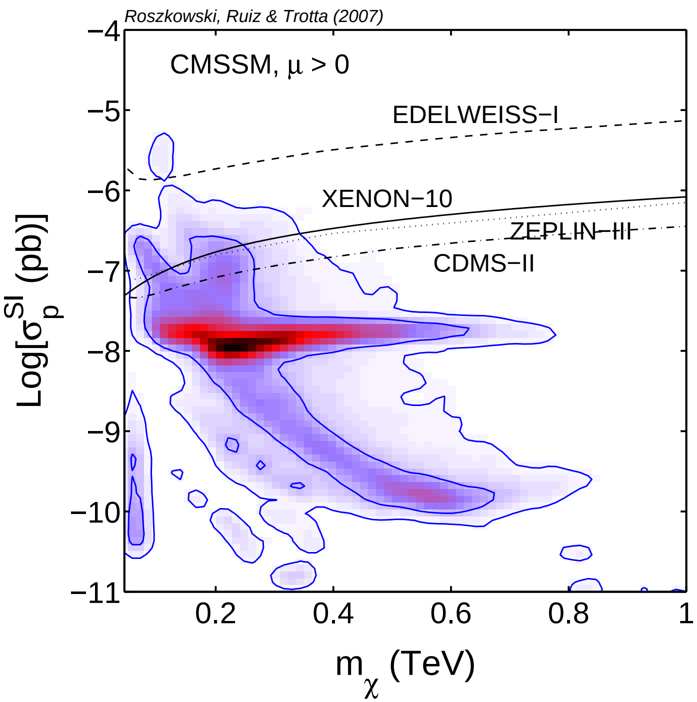

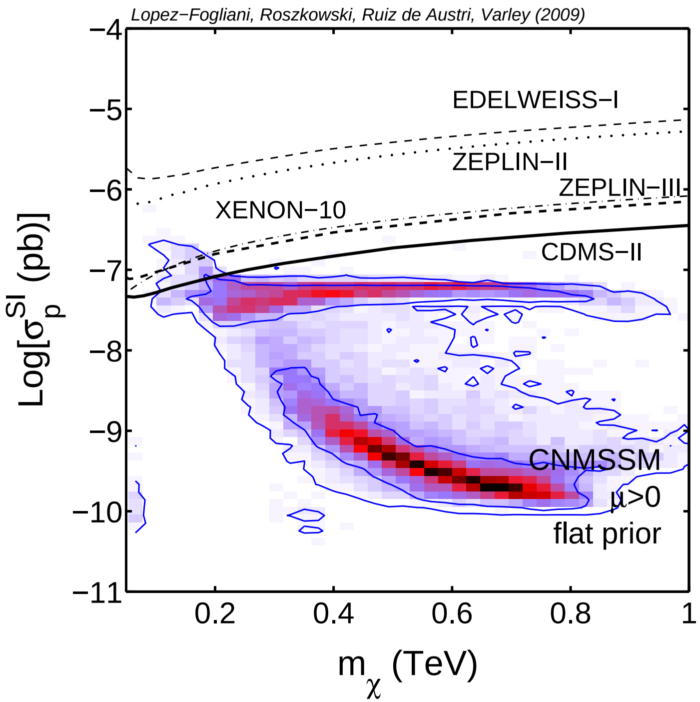

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⇒ fairly similar pattern

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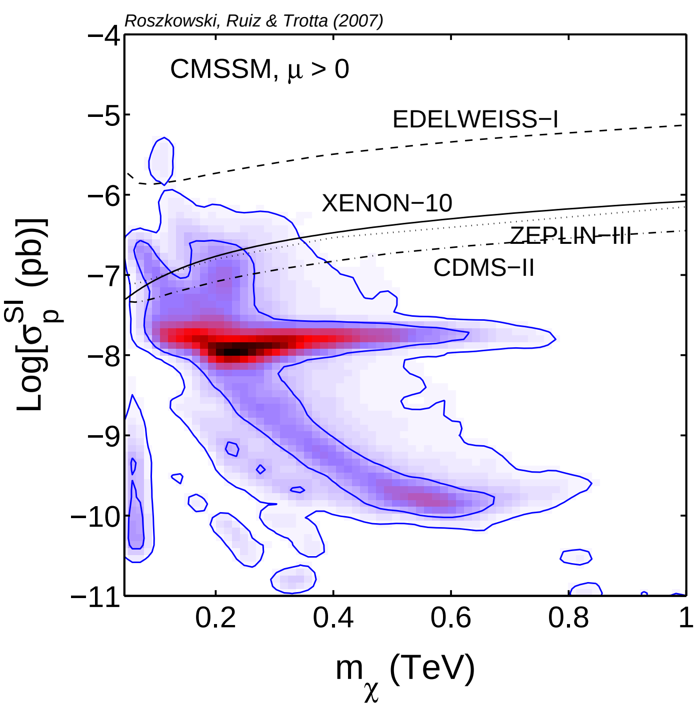

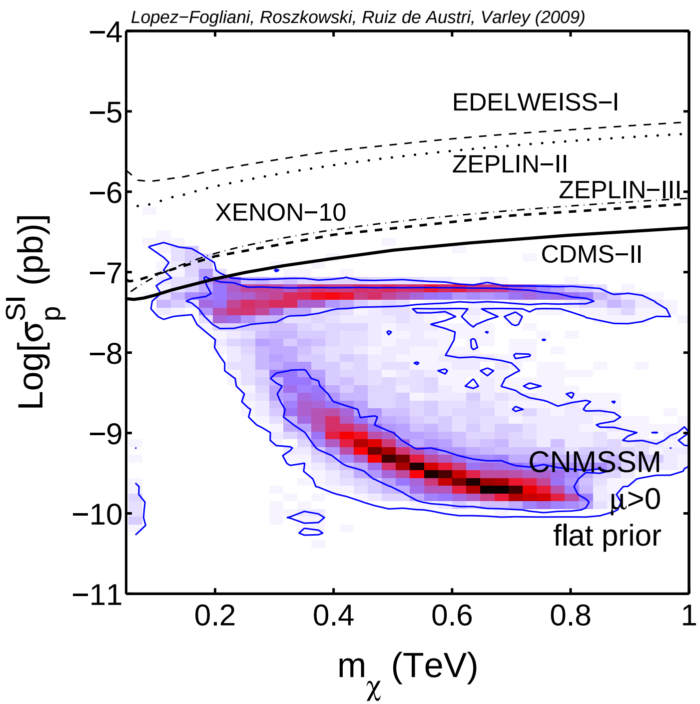

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many collider signatures also (likely to be) similar

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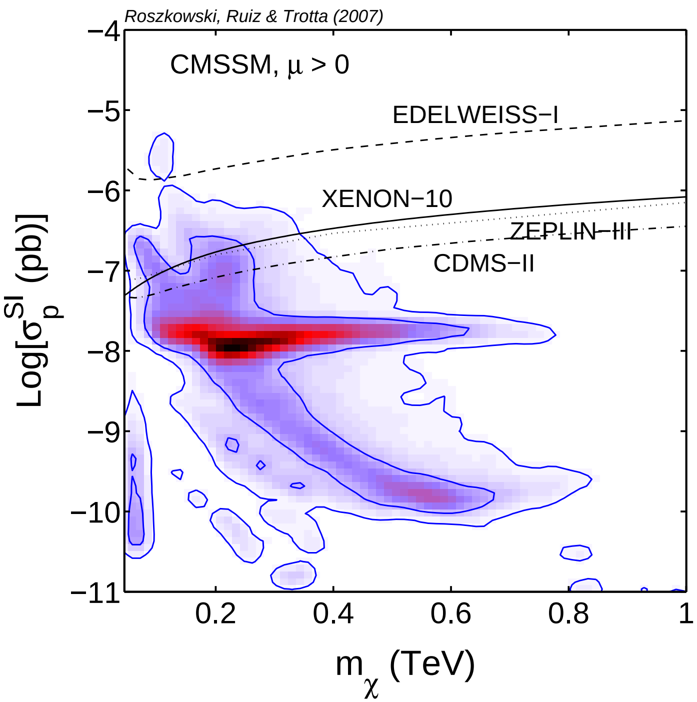
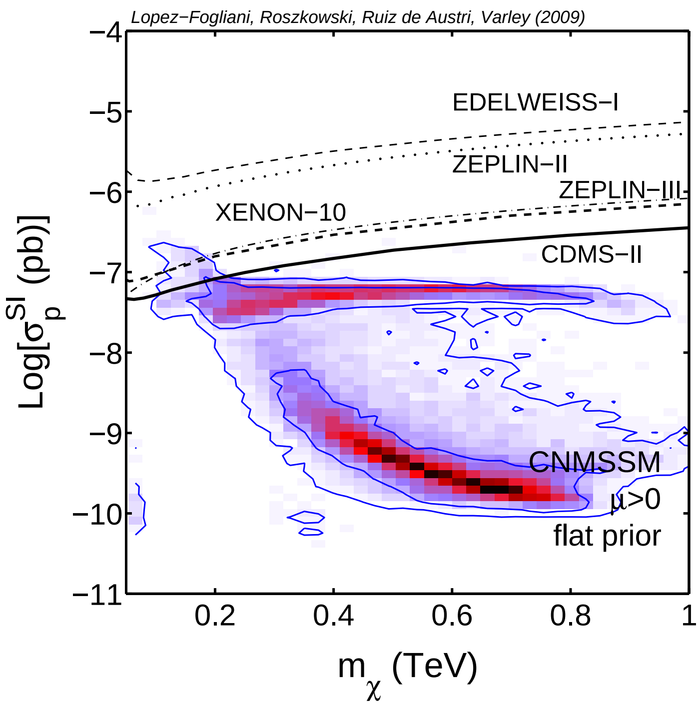
Higgs: H_u, H_d and singlet S; λS^3

Constrained MSSM (mSUGRA)





singlino DM very rare

$\Rightarrow$ fairly similar pattern

many collider signatures also (likely to be) similar

$\Rightarrow$ LHC, DM expt: it may be hard to discriminate among SUSY models

Gazing into a crystal ball...

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Assume SUSY...

WIMP detected in DM expts and SUSY found at the LHC

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...life may not follow the favored script...

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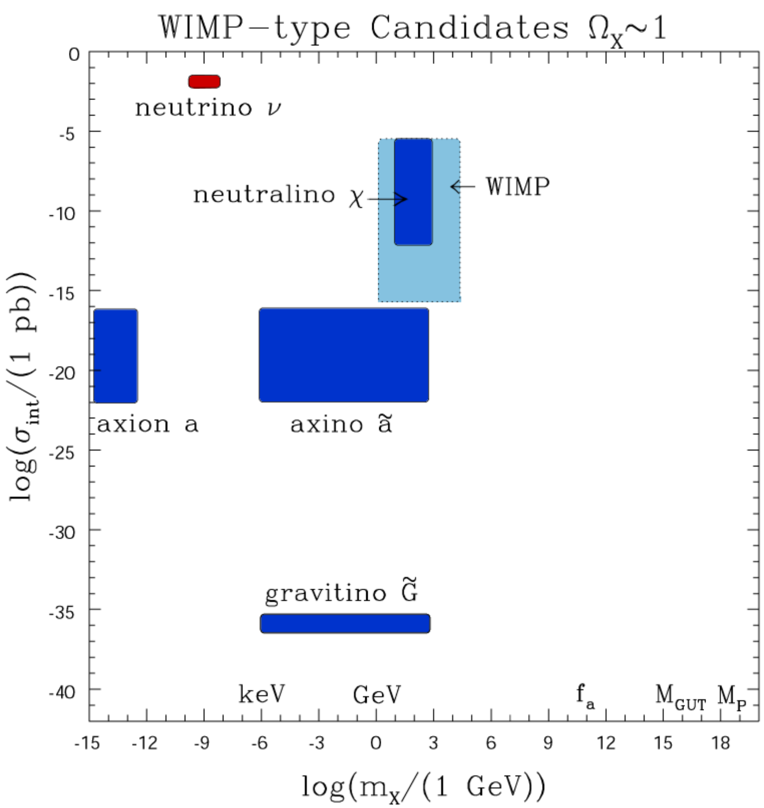
...possibly for a very long time

The Big Picture

well–motivated particle candidates such that $\mathbf{\Omega \sim 0.1}$



- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\tilde{a}$
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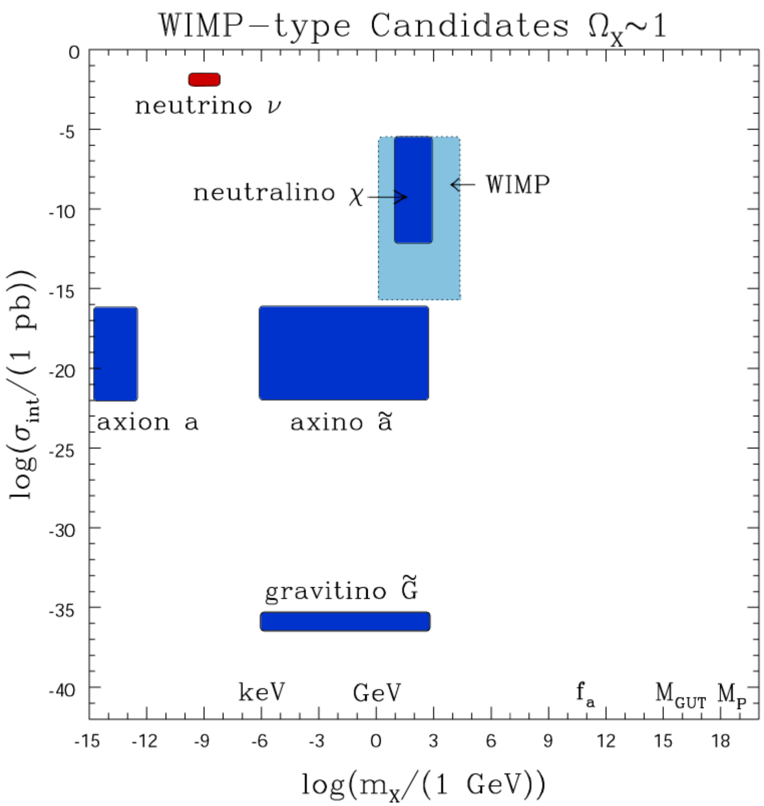

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axino, gravitino EWIMPs are well-motivated

- natural theoretical frameworks (SUSY+axion, SUSY+gravity)
- relic density often $\sim \mathbf{0.1}$

E–WIMPs: $\widetilde{G}$ and $\widetilde{a}$

(extremely weakly interacting massive particles)

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(assume usual gravity mediated SUSY breaking)

	axino $\widetilde{a}$	gravitino $\widetilde{G}$
spin	1/2	3/2
interaction	$\sim 1/f_a^2$	$\sim 1/M_{\rm P}^2$
mass	$\not\propto M_{\rm SUSY}$	$\propto M_{\rm SUSY}$

- mass model dependent

  take it as free parameter

  $\sim$ eV $-$ 100 TeV

$f_a \sim 10^{9-12}\,\mathrm{GeV}$ – PQ scale
$M_{\rm P} = 2.4\times 10^{18}\,\mathrm{GeV}$ – reduced Planck mass
$M_{\rm SUSY} \sim 100\,\mathrm{GeV} - 1\,\mathrm{TeV}$ – soft SUSY mass scale

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R-parity can but does not have to be conserved

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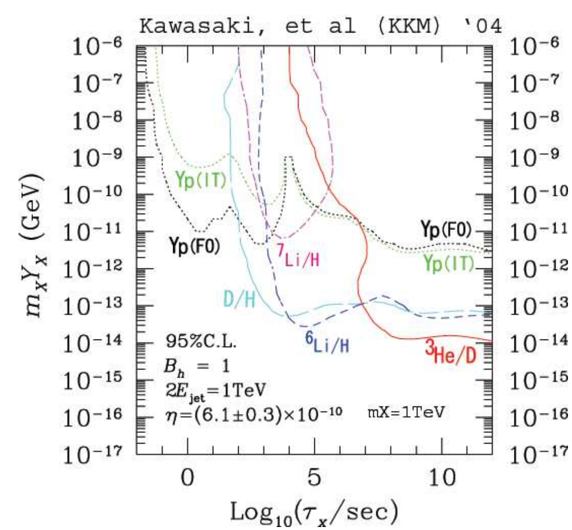

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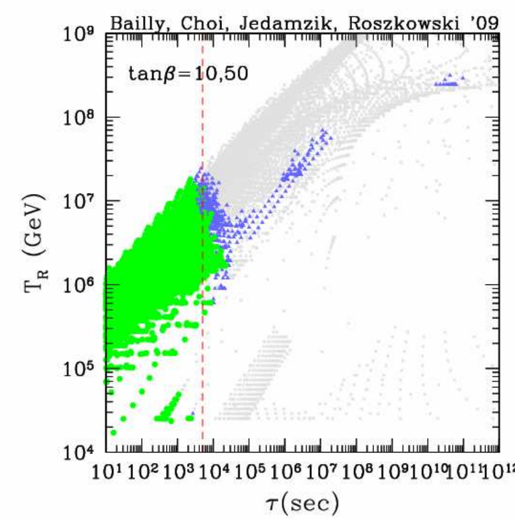
10^{11} sec if $^6\mathrm{Li}/^7\mathrm{Li}$ relaxed



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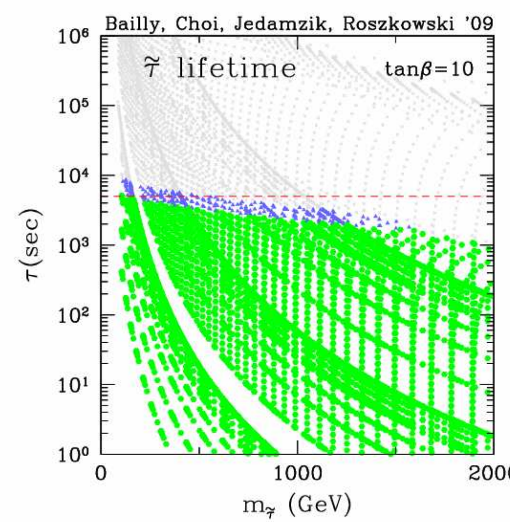

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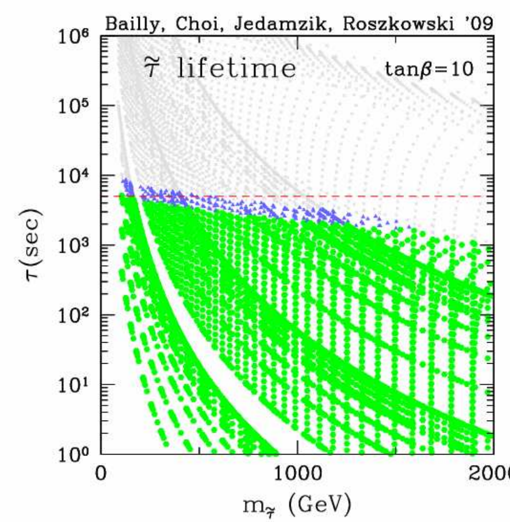

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$\Rightarrow$ spectacular signature at the LHC

LHC: may give unique insight into EWIMP-type DM

EWIMPs $\widetilde{a}$ and $\widetilde{G}$ as DM?

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- both $\widetilde{a}$ and $\widetilde{G}$ are viable DM candidates (cold, warm)

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$\Rightarrow$ **LHC can give strong indications for EWIMP as DM**

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- $\widetilde{a}$ or $\widetilde{G}$ LSP: determine reheating temperature T_R

  Choi, LR, Ruiz de Austri, arXiv:0710.3349
  see also Endo, Hamaguchi, Nakaji, arXiv:1008.2307

The message:

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In revealing the nature of the dark matter in the Universe, the role of the LHC will not be just helpful, or complimentary.

It will be absolutely essential!

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- this year

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- this year
- or this decade
- or this century
- or ...

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