Neutralino Dark Matter and Bayesian Statistics

Leszek Roszkowski

Astro–Particle Theory and Cosmology Group

Sheffield, England

with Roberto Ruiz de Austri and Roberto Trotta

hep-ph/0602028 $\longrightarrow$ JHEP06, hep-ph/0611173 $\longrightarrow$ JHEP07

arXiv:0705.2012 $\longrightarrow$ JHEP07

arXiv:0707.0622 (with R.R., R.T. and J. Silk)

and arXiv:0809.3792 (with R.R., R.T., F. Feroz and M. Hobson)

and in preparation with R.R, R.T, T. Varley and S. Tsai

new tool: SuperBayes package, available from www.superbayes.org

Dark Matter Programme at GGI

Dark Matter Programme at GGI

- venue: Galileo Galilei Institute, Florence
- dates: May - June 2010
- organizers: H. Baer, L. Covi,
  L. Roszkowski and P. Ullio

Cosmology After WMAP...

Post WMAP-5yr (April 08) ...+ACBAR+CBI+SN+LSS+... $\Omega_i = \rho_i / \rho_{crit}$

Hubble $H_0 = 100\, h$ km/ s/ Mpc

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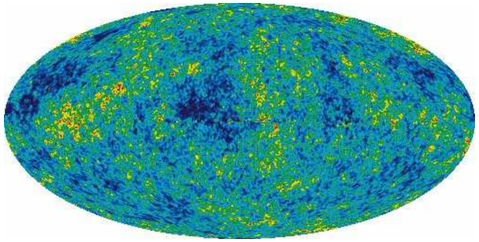
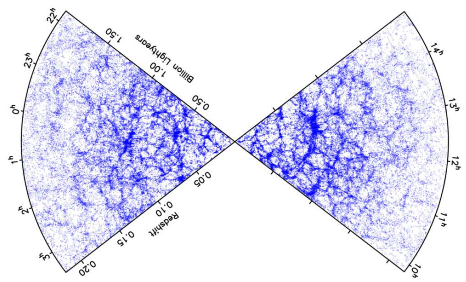
assume simplest ΛCDM model

- matter $\Omega_{\rm m} h^2 = 0.1378 \pm 0.0043$
- baryons $\Omega_{\rm b} h^2 = 0.02263 \pm 0.00060$
- $\Rightarrow$ $\boxed{\Omega_{\rm CDM} h^2 = 0.1152 \pm 0.0042}$
- $h = 0.696 \pm 0.017$
- $\Omega_\Lambda = 0.715 \pm 0.20 \ldots$

CMB (WMAP, ACBAR, CBI,...)



LSS (2dF, SDSS, Lyman-α)



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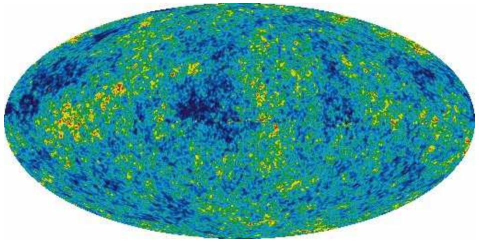

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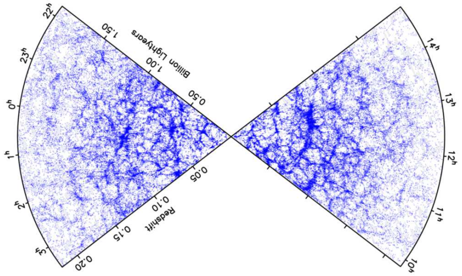
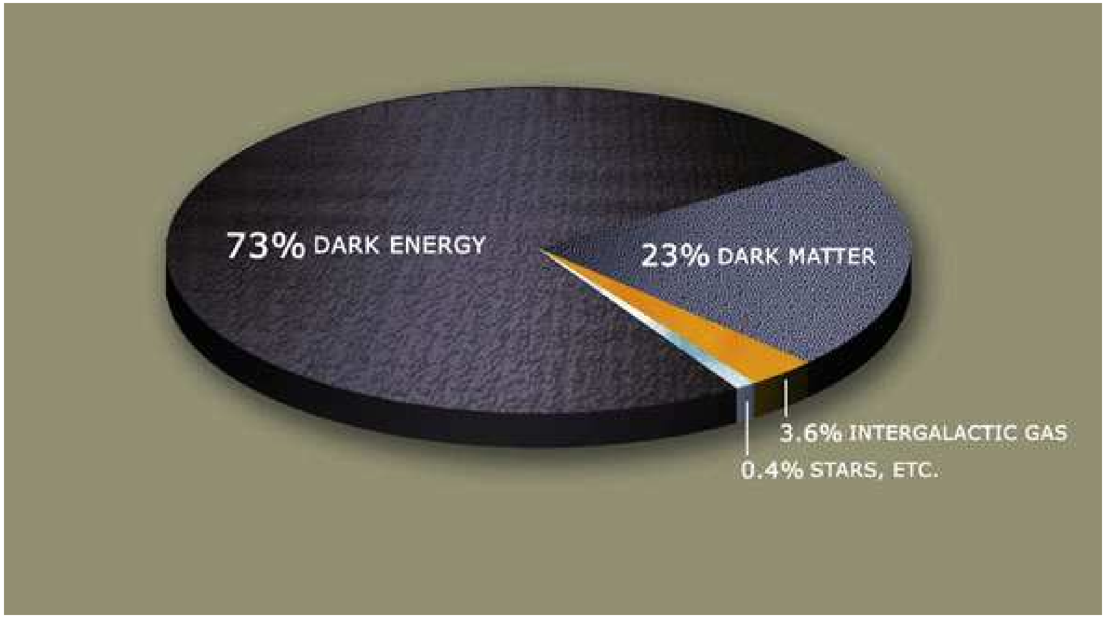


- concordance model works well
- main components: dark energy and dark matter

Cosmic Pie


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

Outline

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- DM candidates and particle physics models

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- summary

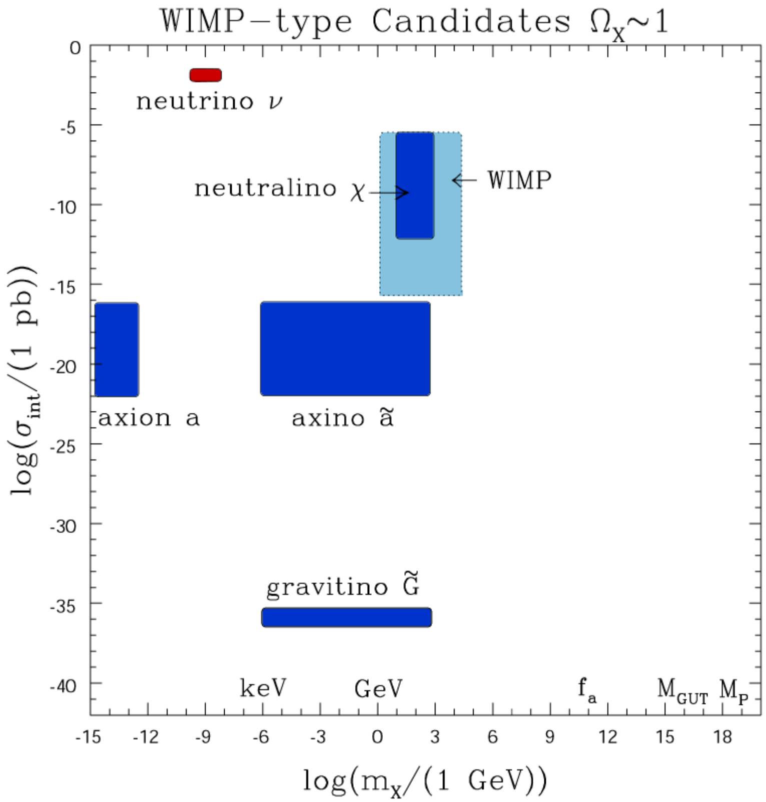
DM: The Big Picture

* – 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

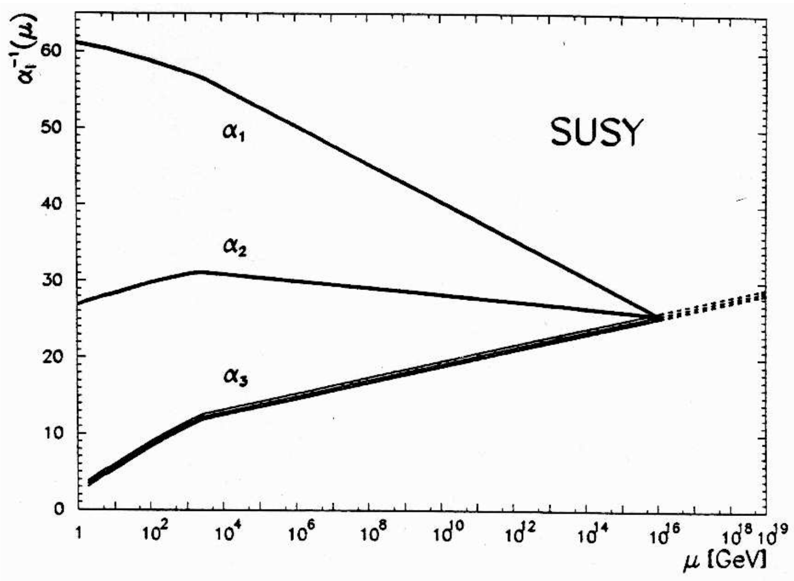


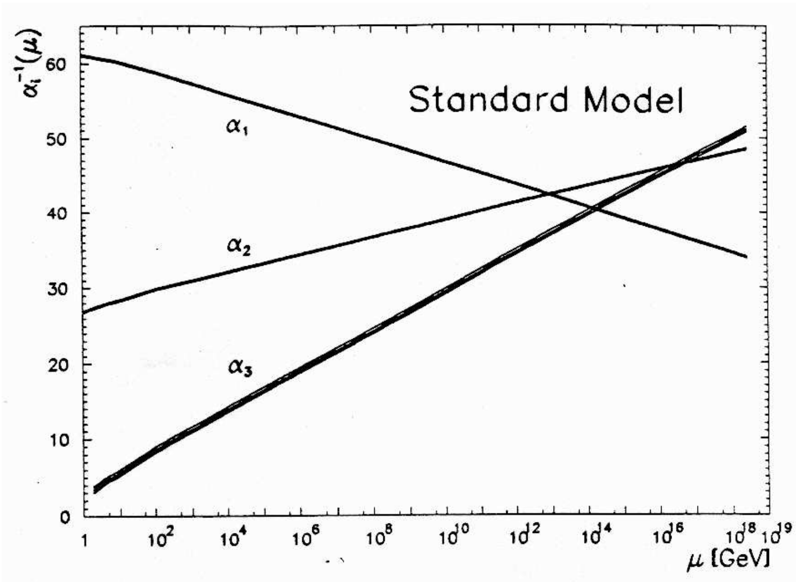
- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$

- vast ranges of interactions and masses
- different production mechanisms in the early Universe (thermal, non-thermal)
- axino, gravitino could be either CDM or WDM (or both)
- need to go beyond the Standard Model

To SUSY or not to SUSY?

SUSY - by far the most popular and developed framework





gauge couplings "run" with energy

Neutralino of SUSY – Prime Suspect

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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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Don't forget:

- multitude of SUSY-based models: general MSSM, CMSSM, split SUSY, MNMSSM, $SO(10)$ GUTs, string inspired models, etc, etc
- neutralino properties often differ widely from model to model

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neutralino = stable, weakly interacting, massive $\Rightarrow$ WIMP

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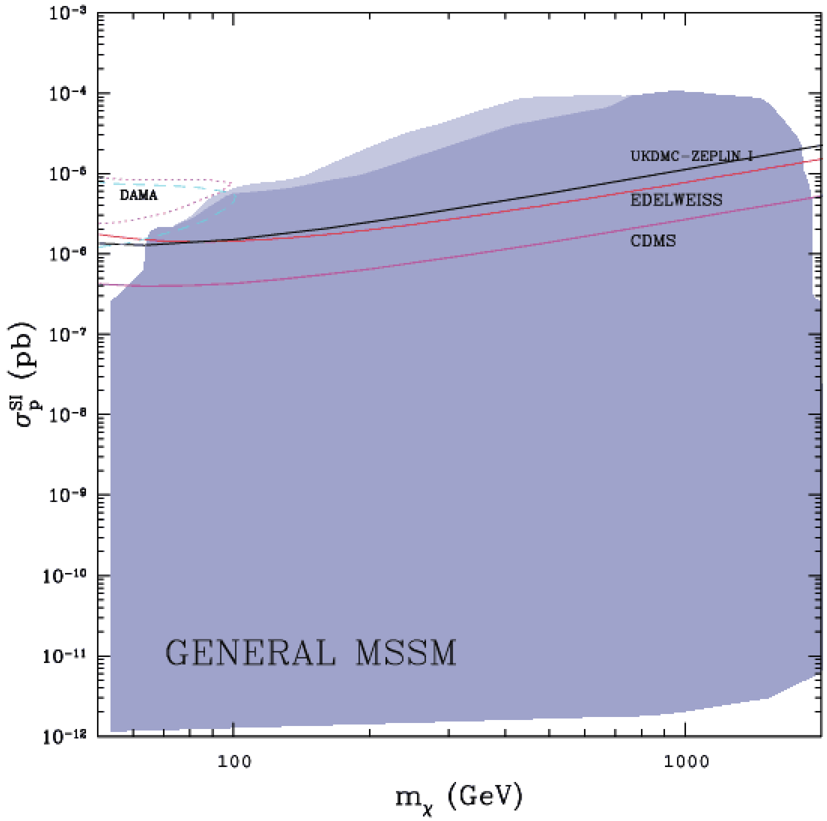
- other ideas: traces of WIMP annihilation in dwarf galaxies, in rich clusters, etc

  more speculative

MSSM: Expectations for σ_p^{SI}

general MSSM $\mu > 0$

Kim, Nihei, LR & Ruiz de Austri (02)



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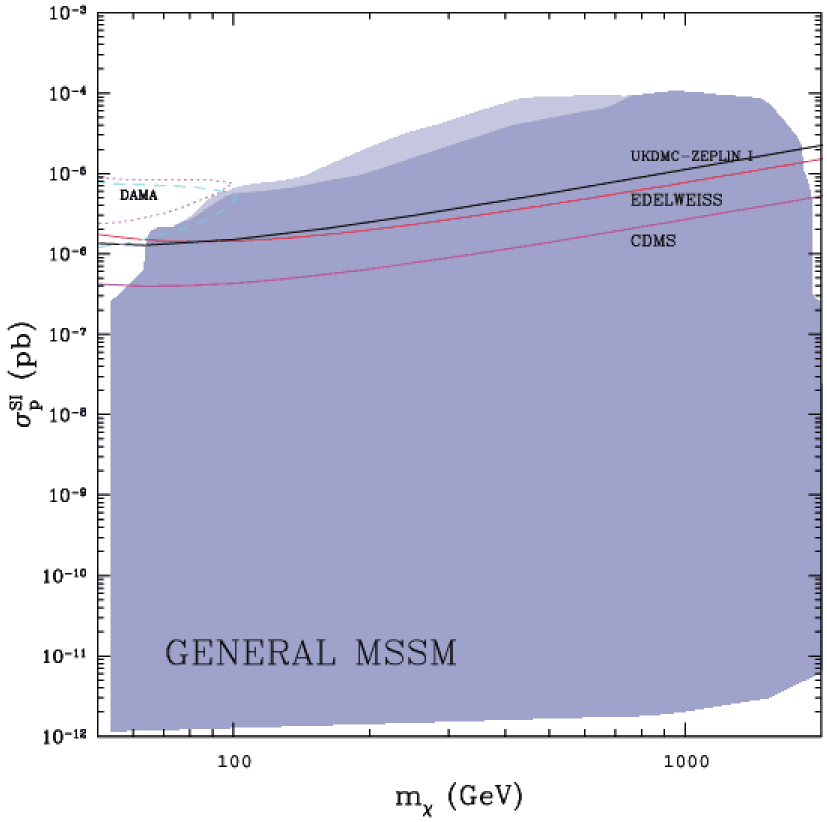

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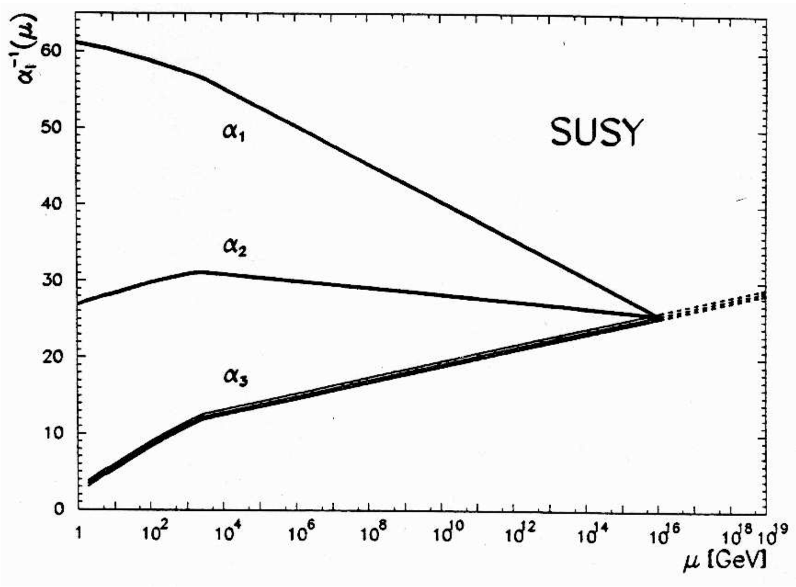
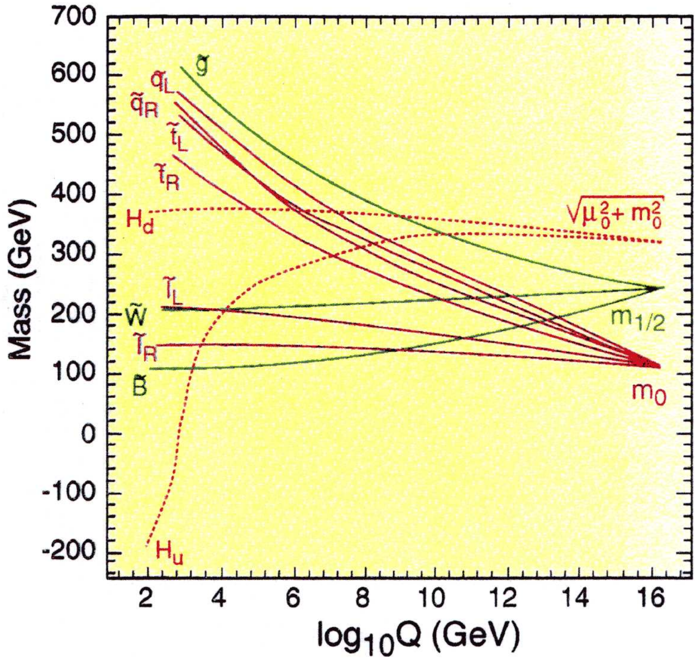
$\Rightarrow$ MSSM: vast ranges! Lacks real predictive power!

Add grand unification...



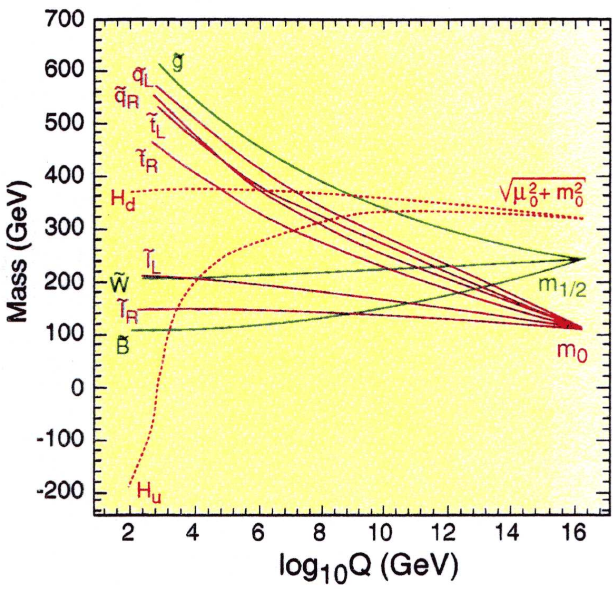


Constrained MSSM (CMSSM)

Kane, Kolda, LR, Wells (1993)

..."benchmark framework" for the LHC

(...e.g., mSUGRA)



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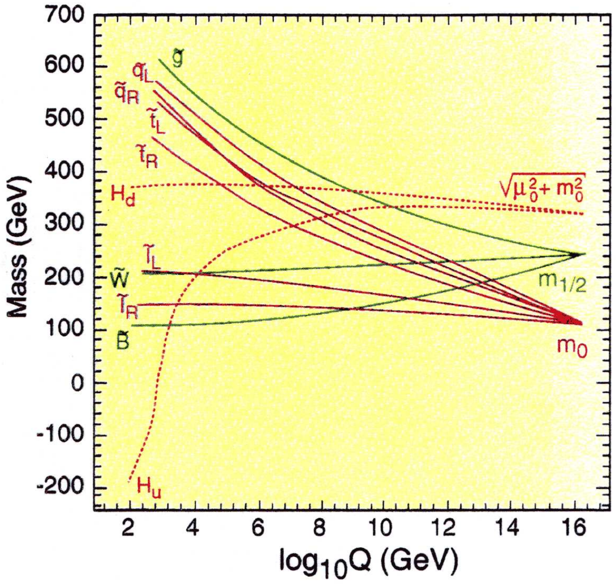

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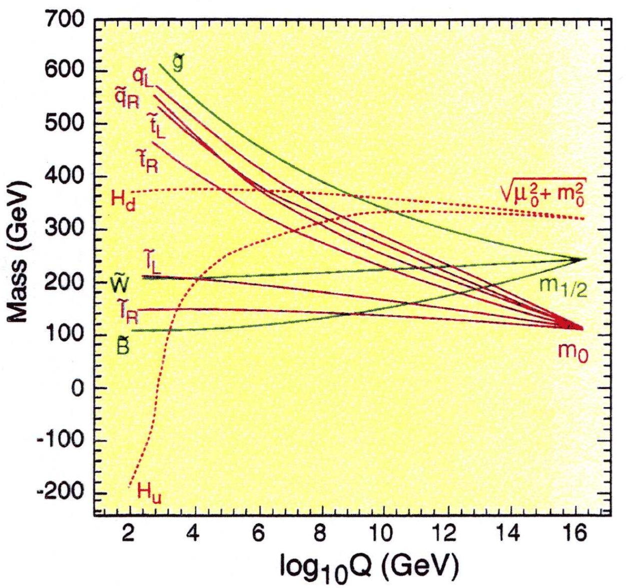

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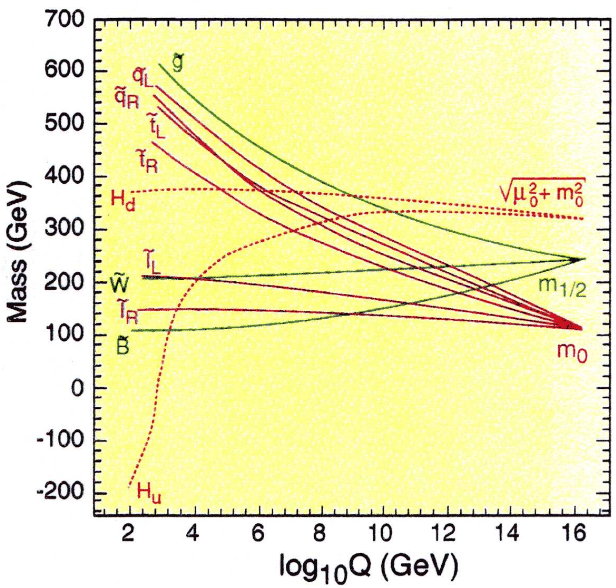

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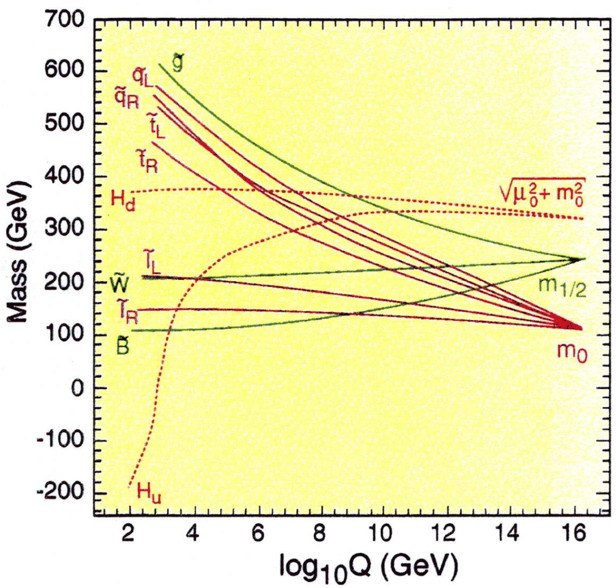

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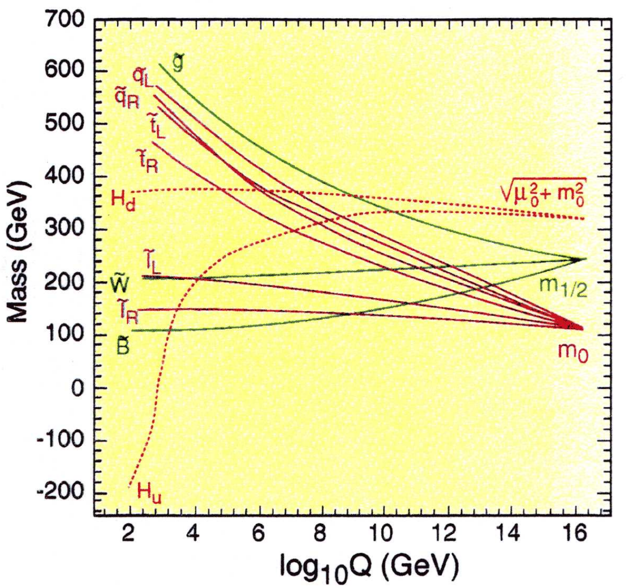

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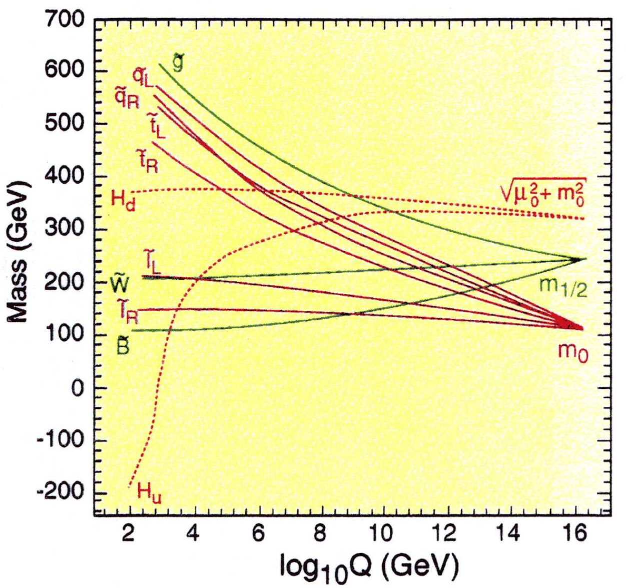

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some useful mass relations:

- bino: $m_\chi \simeq 0.4 m_{1/2}$
- gluino $\tilde{g}$: $m_{\tilde{g}} \simeq 2.7 m_{1/2}$
- supersymmetric tau (stau) $\tilde{\tau}_1$: $m_{\tilde{\tau}_1} \simeq \sqrt{0.15 m^2_{1/2} + m_0^2}$

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very many papers

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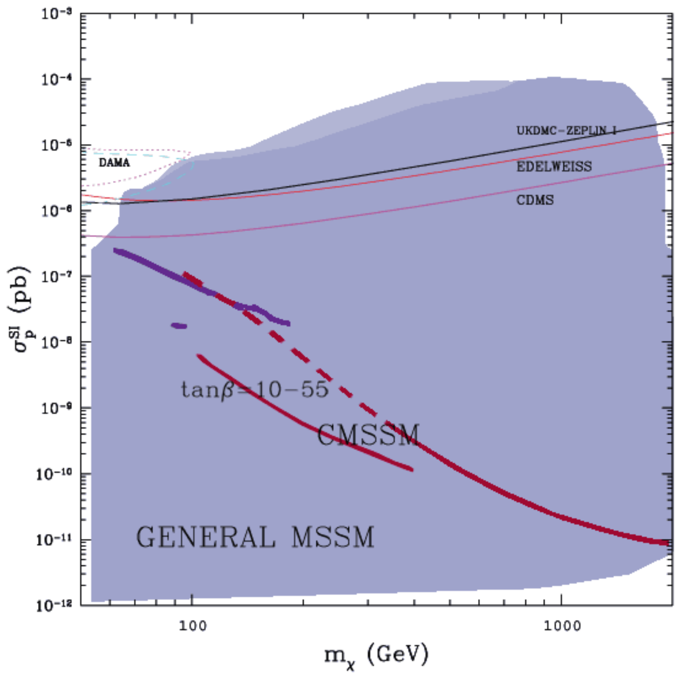
hep-ph/0404052



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- hard to compare relative impact of various constraints,
- hard to include TH + residual SM errors, etc.
- full scan of PS not feasible
- impossible to assess relative impact of various constraints

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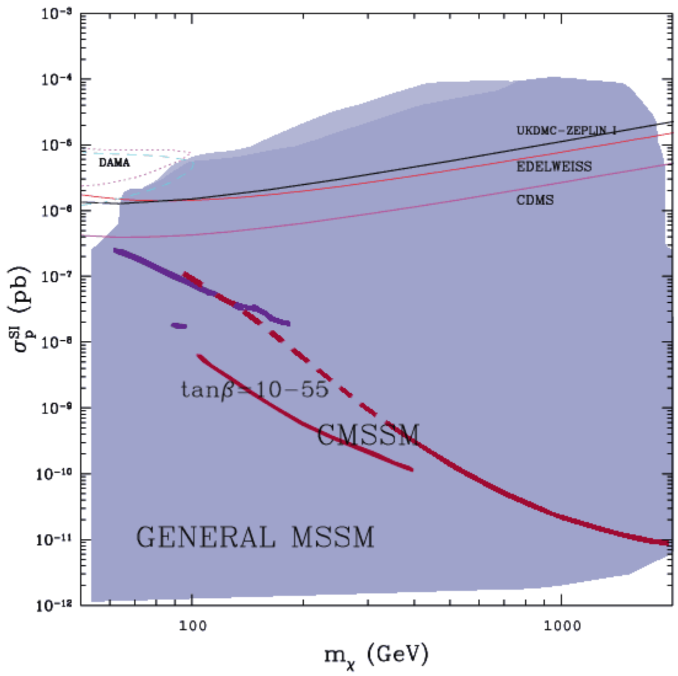

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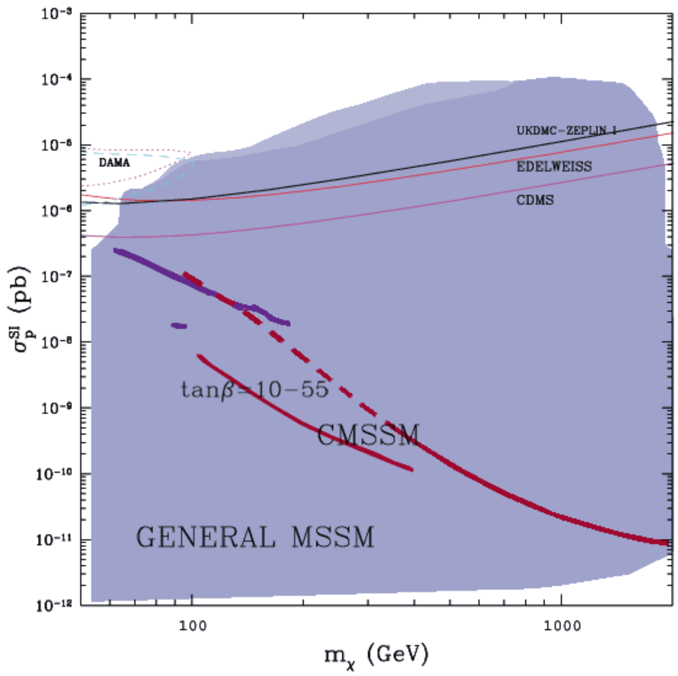

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results in over-simplified predictions

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- relevant SM param's $\boxed{\psi = M_t, m_b(m_b)^{\overline{MS}}, \alpha_s^{\overline{MS}}, \alpha_{\mathrm{em}}(M_Z)^{\overline{MS}}}$

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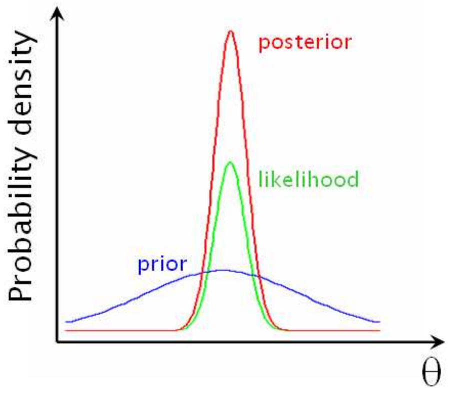

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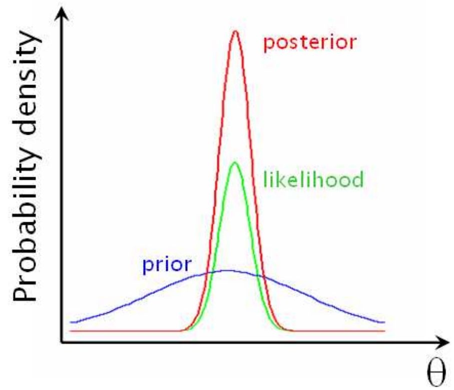
$$p(\theta, \psi | d) = \frac{p(d|\xi)\pi(\theta,\psi)}{p(d)}$$



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- $p(d)$: evidence (normalization factor)

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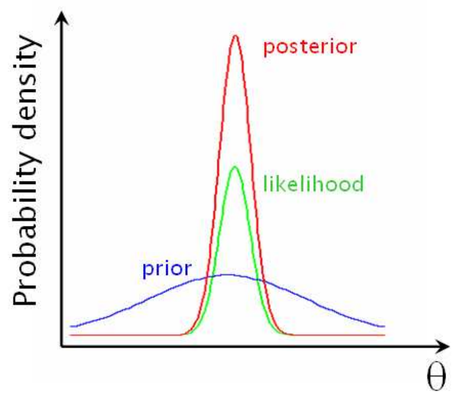

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- usually marginalize over SM (nuisance) parameters ψ $\Rightarrow$ $p(\theta|d)$

Impact of varying SM parameters

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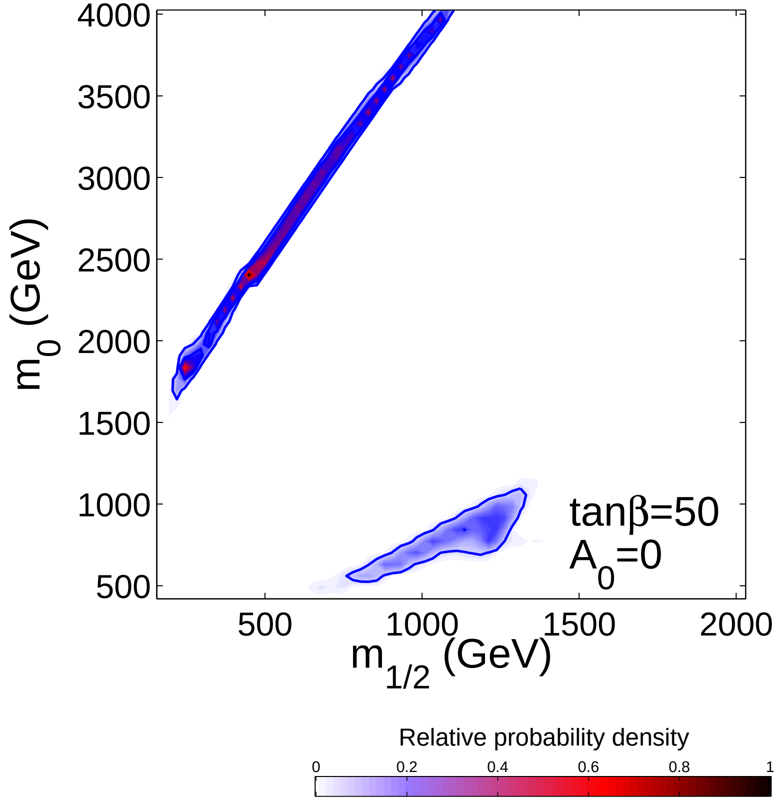
fix $\tan\beta$, A_0 + all SM param's



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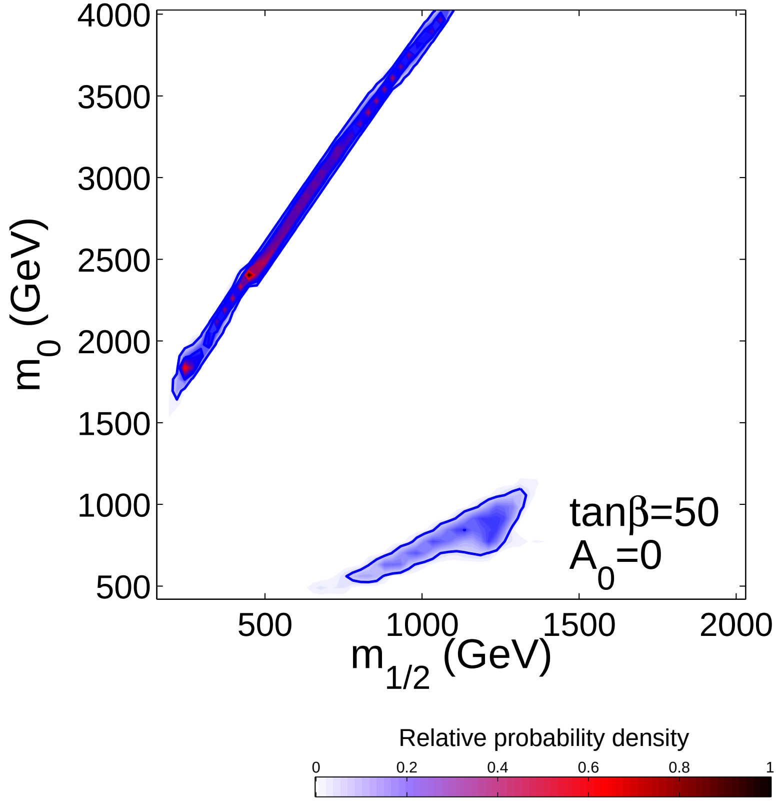
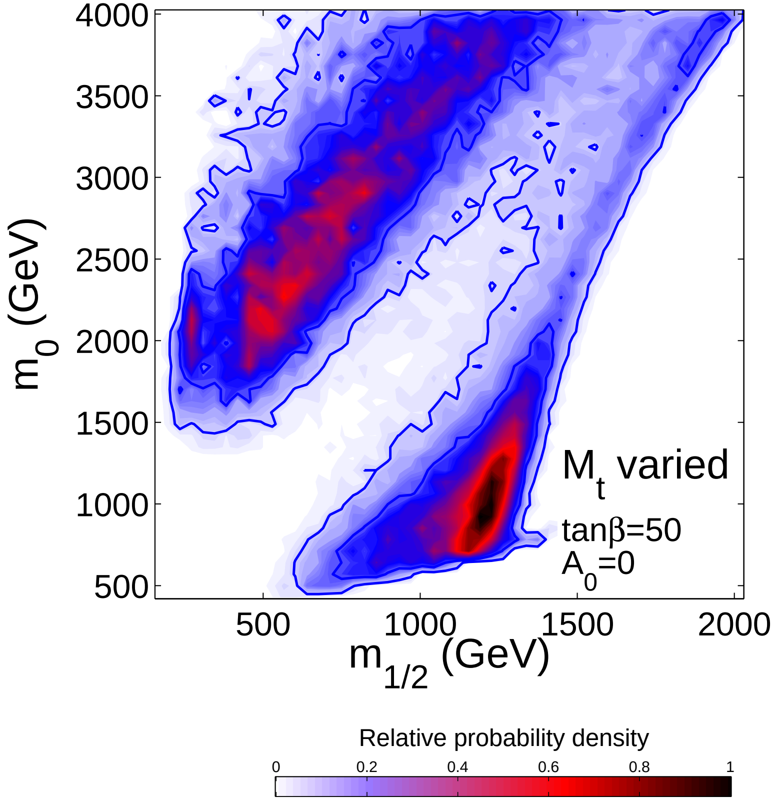


vary M_t



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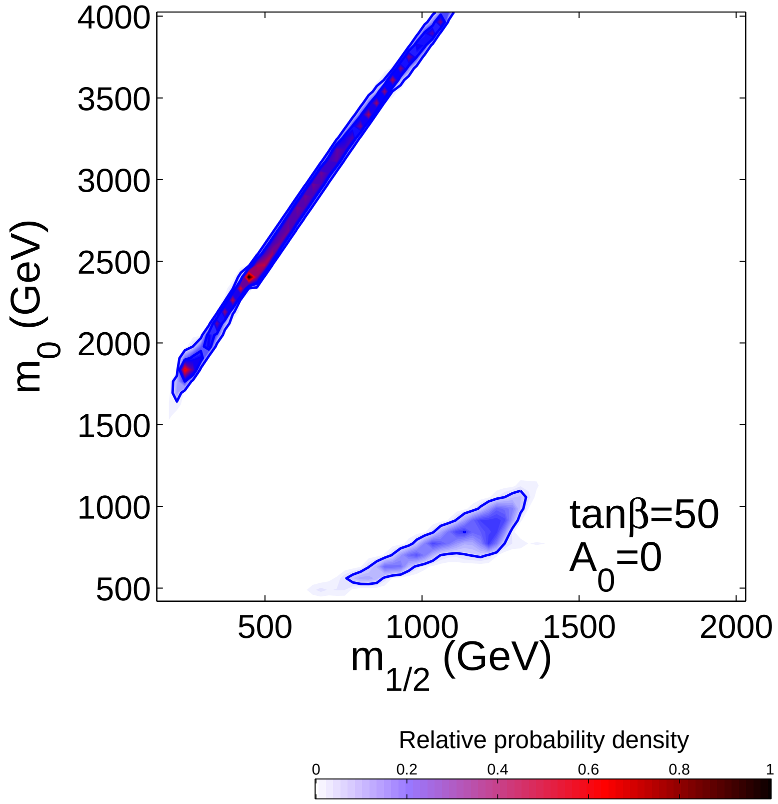
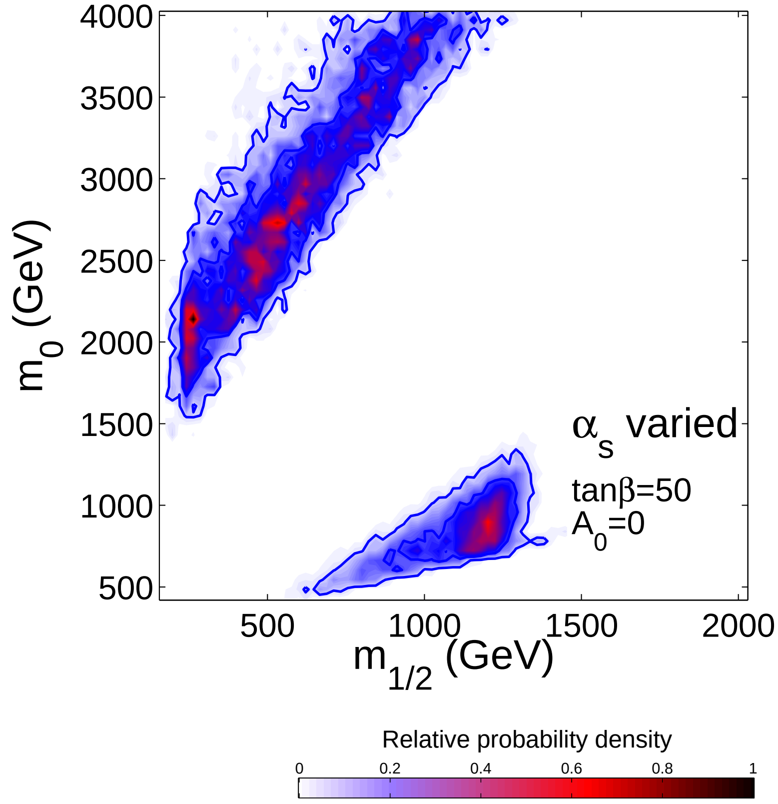


vary α_s



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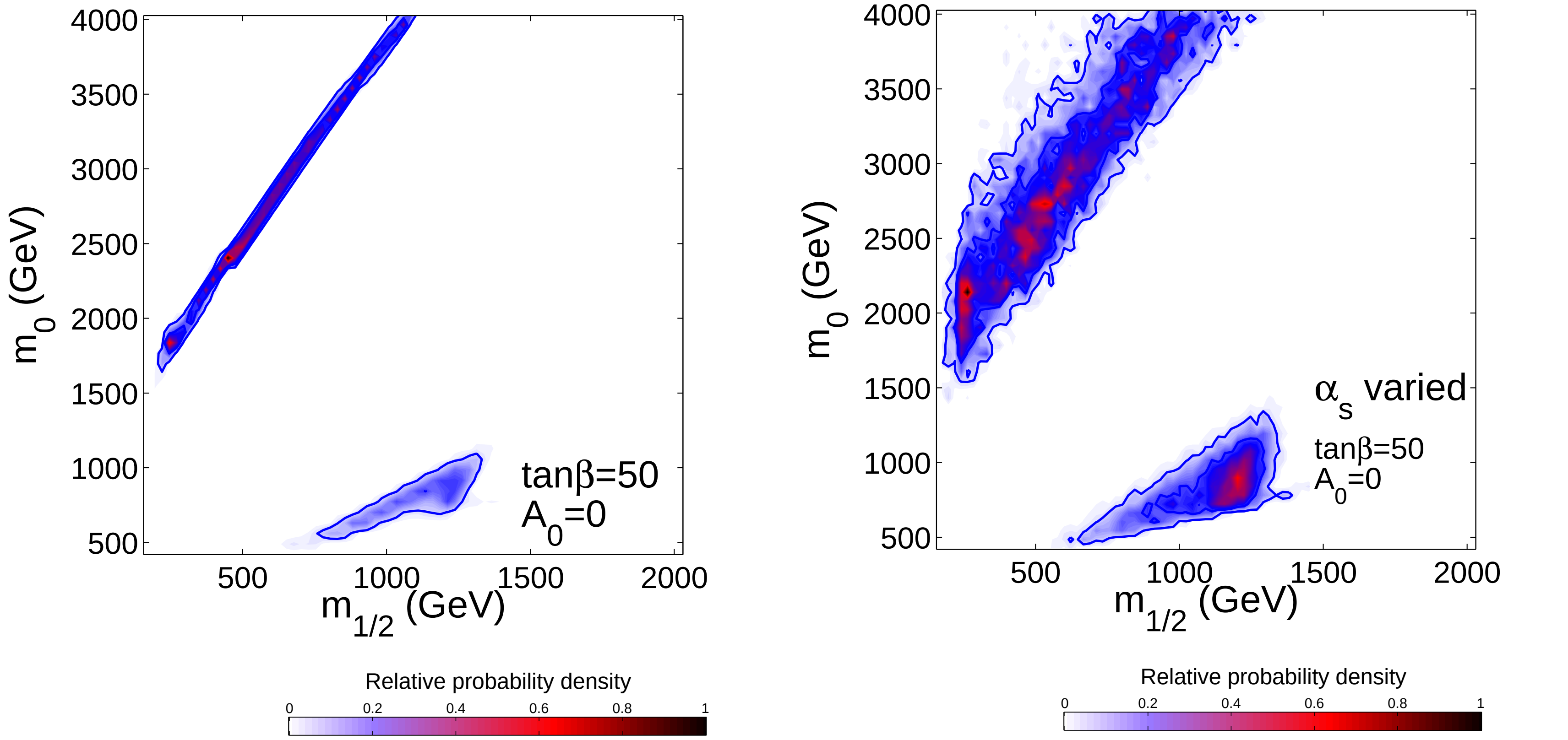
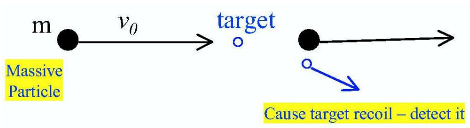


residual errors in SM parameters $\Rightarrow$ strong impact on favoured SUSY ranges

effect of varying A_0, $\tan\beta$ also substantial

CMSSM: Prospects for direct detection

CMSSM: Constrained MSSM



Bayesian analysis, flat priors, MCMC

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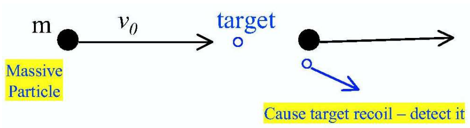

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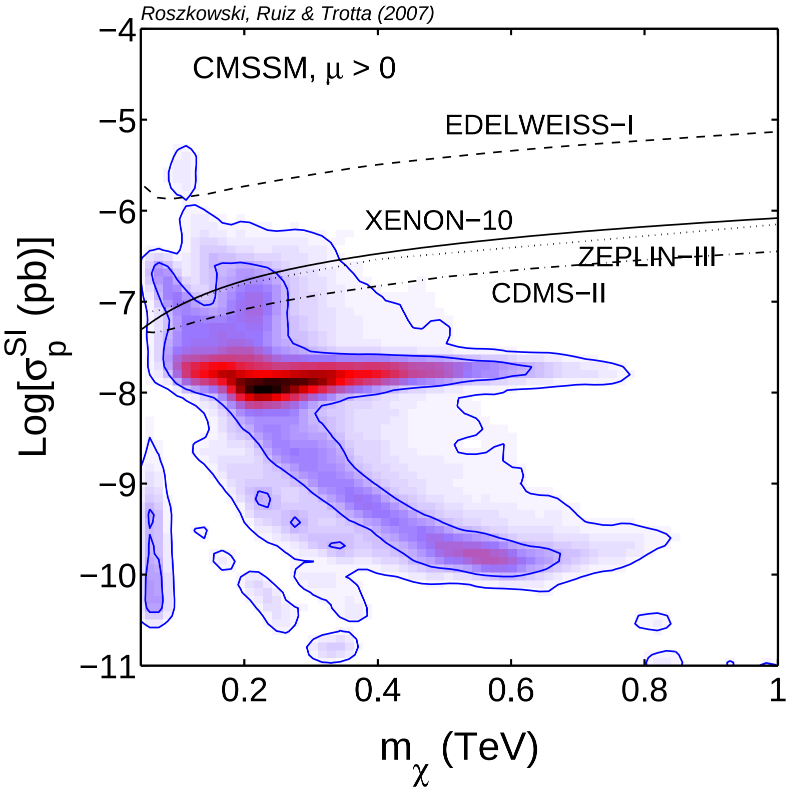

internal (external): **68%** (**95%**) region

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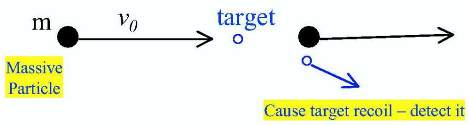

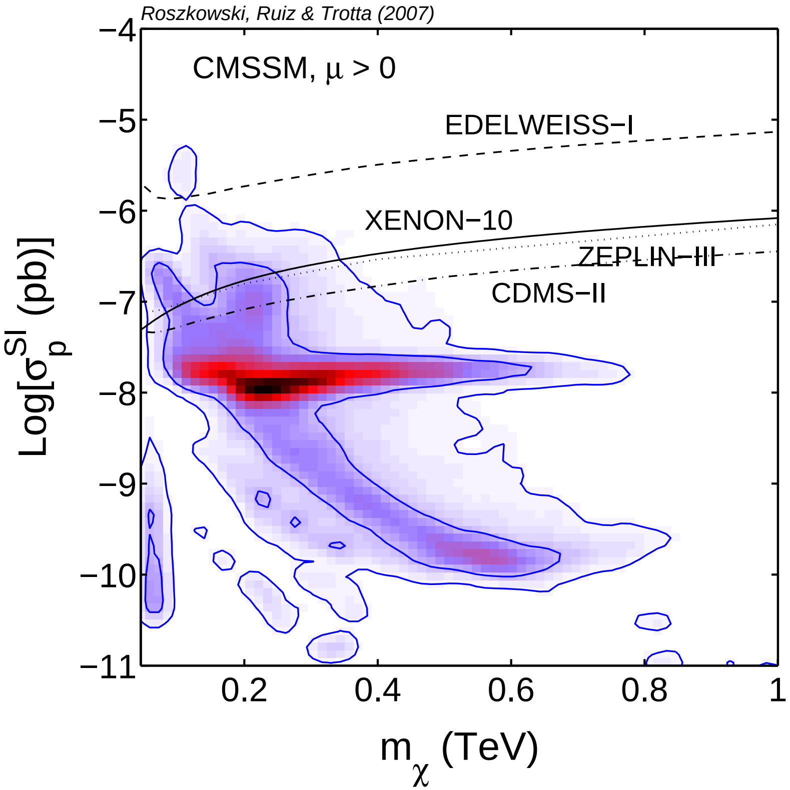

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XENON-10 (June 07) and CDMS-II (Feb 08):

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

also Zeplin–III

$\Rightarrow$ already explore 68% region

(large $m_0 \gg m_{1/2}$ $\Rightarrow$ heavy squarks) largely beyond LHC reach

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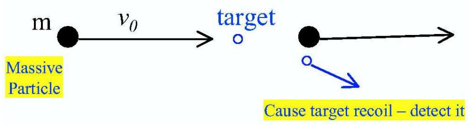

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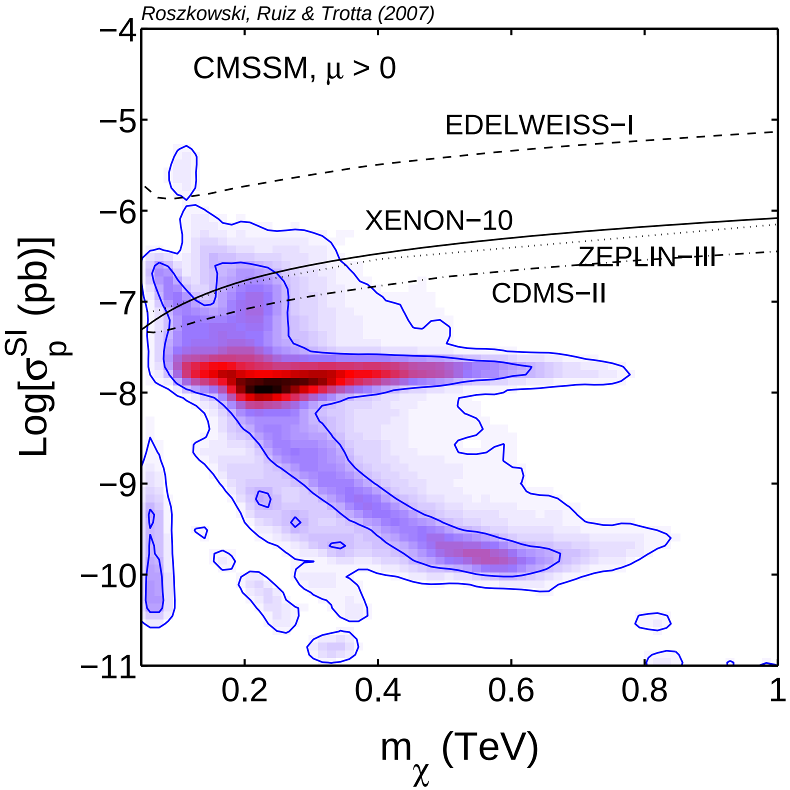

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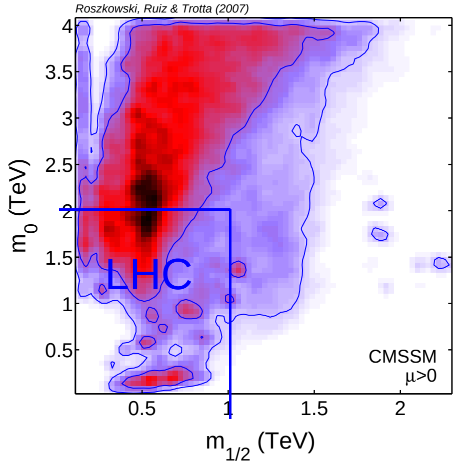

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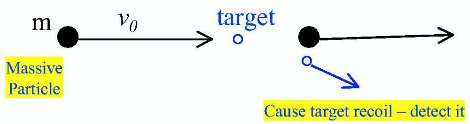

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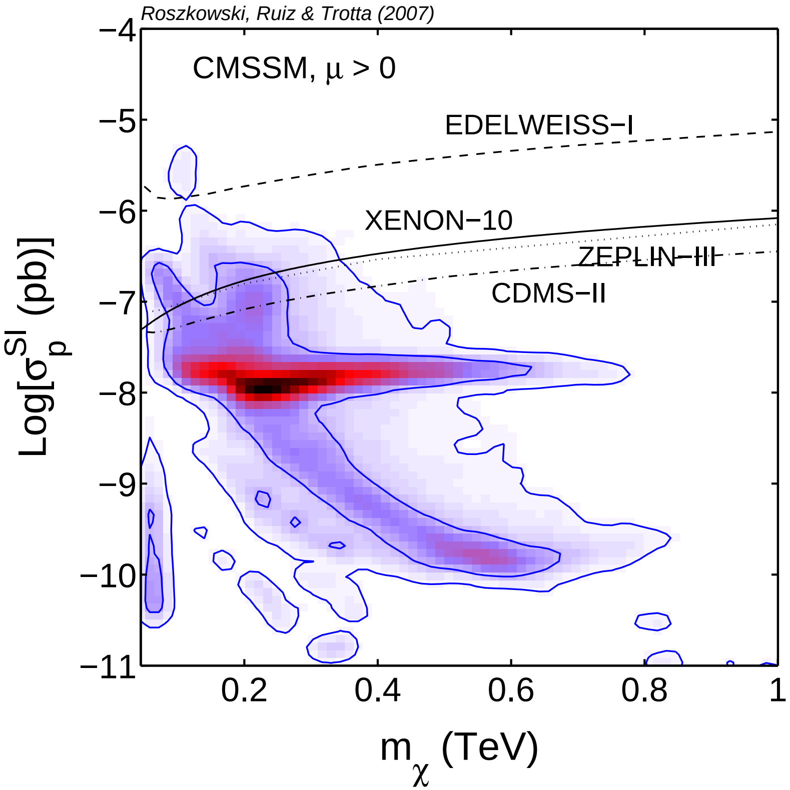

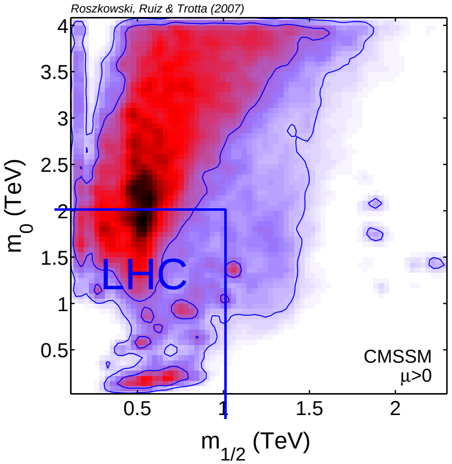

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$\Rightarrow$ DD: prospects look very good

Impact of priors

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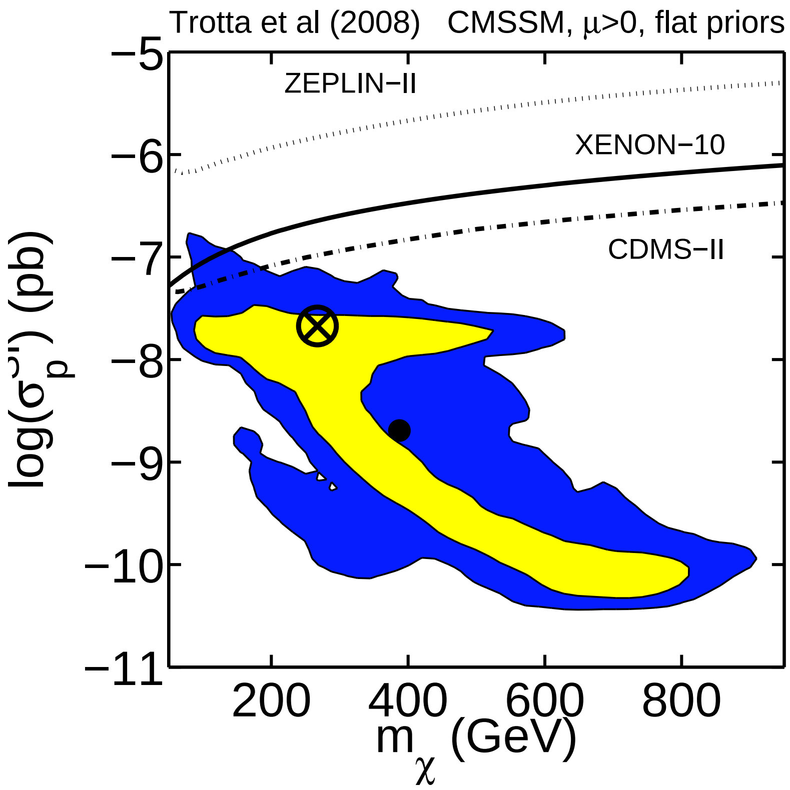
flat in m_0, $m_{1/2}$



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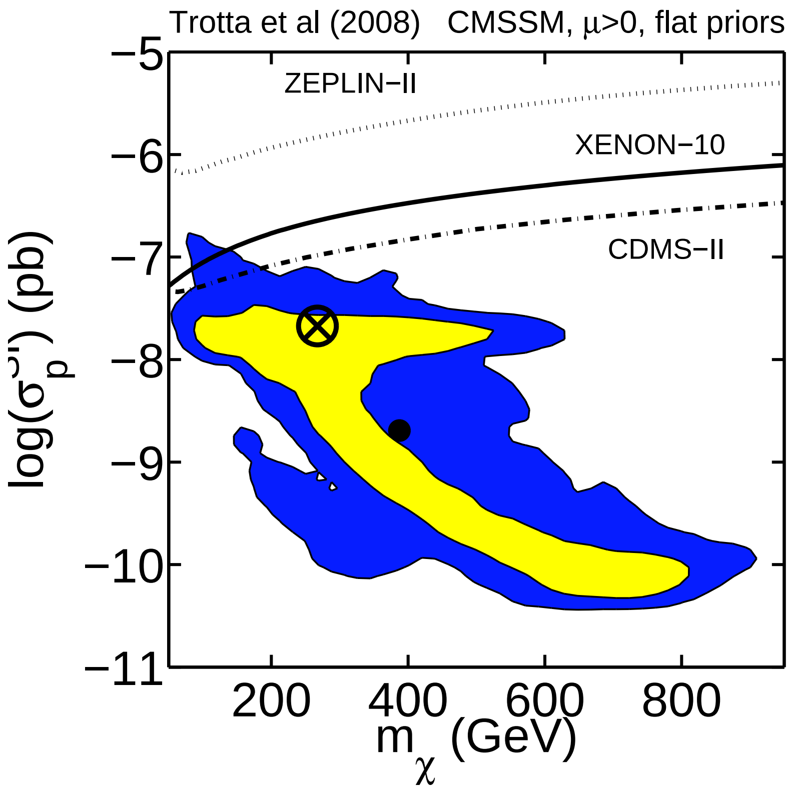
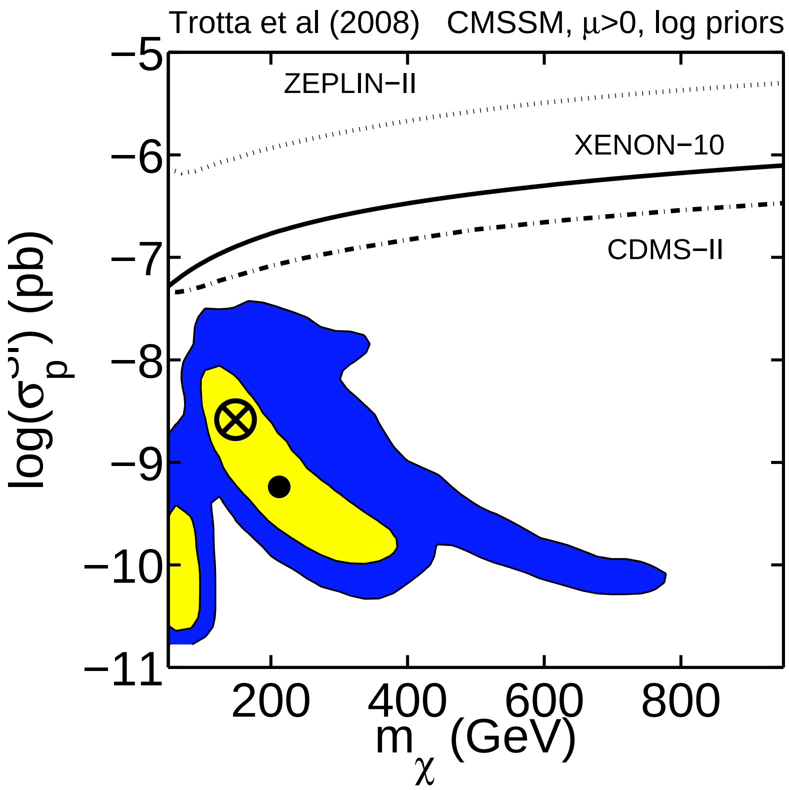


flat in $\log(m_0)$, $\log(m_{1/2})$



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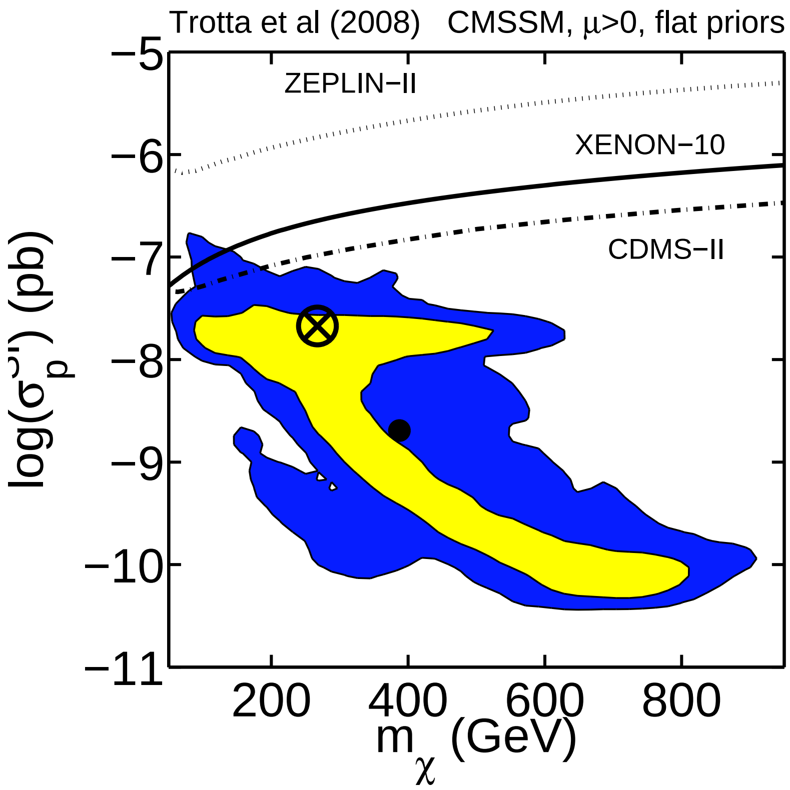

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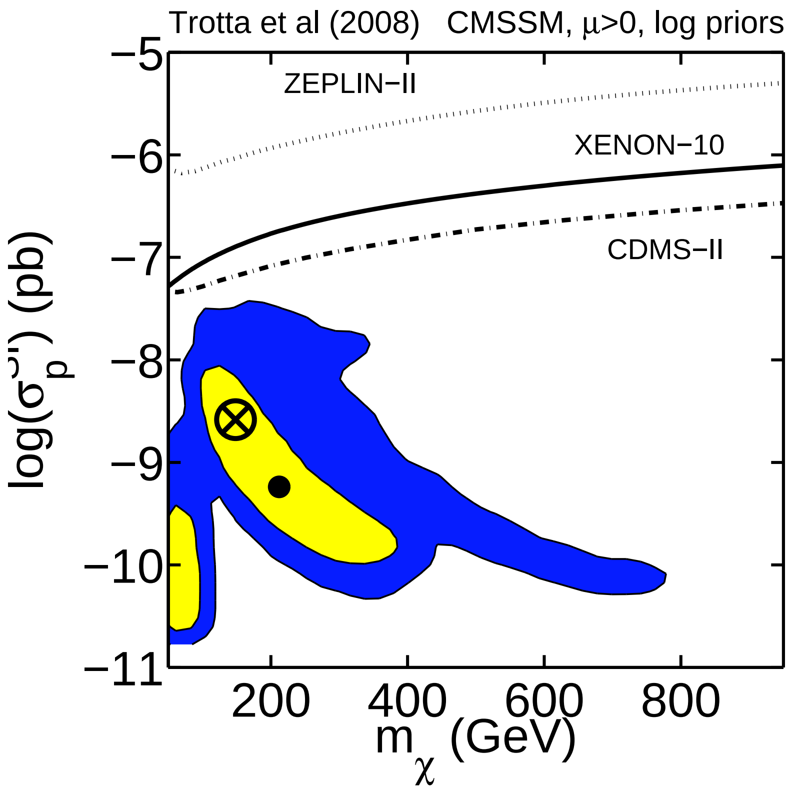

- still strong prior dependence (data not yet constraining enough)
- both priors: most regions above some 10^{-10} pb $\Rightarrow$ good news for DM expt
- LHC reach: $m_\chi \lesssim 400 - 500\,\mathrm{GeV}$ $\Rightarrow$ additional vital info

Non-Universal Higgs Mass (NUHM)

...many papers (Ellis et al, Munoz, et al, Baer et al.)

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At $M_{\rm GUT} \simeq 2 \times 10^{16}\,{\rm GeV}$: disunify Higgs soft masses from other scalars

- gauginos $M_1 = M_2 = m_{\widetilde{g}} = m_{1/2}$ (c.f. MSSM)
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$$\mu^2 = \frac{\left(m^2_{H_d}+\Sigma^{(1)}_d\right)-\left(m^2_{H_u}+\Sigma^{(1)}_u\right)\tan^2\beta}{\tan^2\beta-1} - \frac{m^2_Z}{2}$$

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- 6+1 parameters: $\boxed{\tan\beta,\ m_{1/2},\ m_0,\ m_{H_u},\ m_{H_d},\ A_0,\ {\rm sgn}(\mu)}$

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- 6+1 parameters: $\boxed{\tan\beta,\ m_{1/2},\ m_0,\ m_{H_u},\ m_{H_d},\ A_0,\ {\rm sgn}(\mu)}$
- two more parameters than in CMSSM
- surprisingly rich phenomenological difference with CMSSM

NUHM: DM Searches

spin-independent c.s.

Bayesian posterior probability maps

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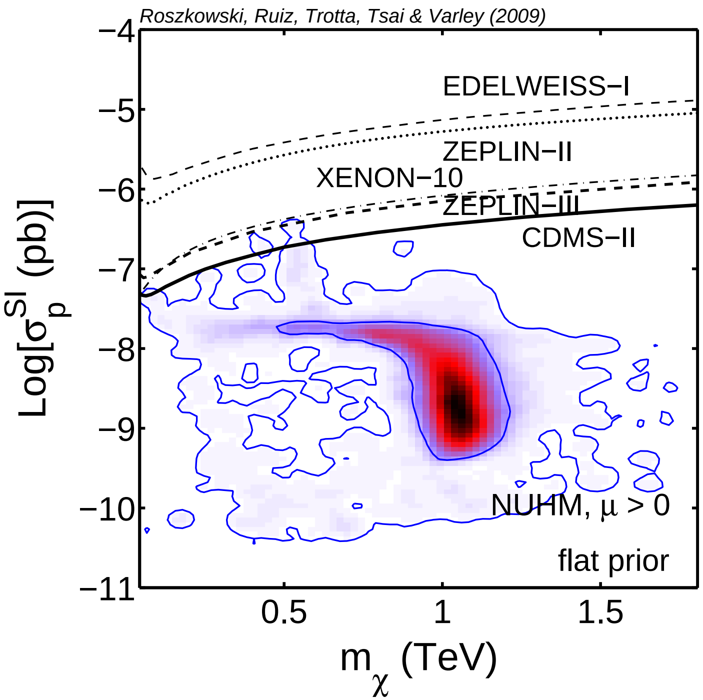
flat prior



large region at $m_\chi \sim 1\,\mathrm{TeV}$

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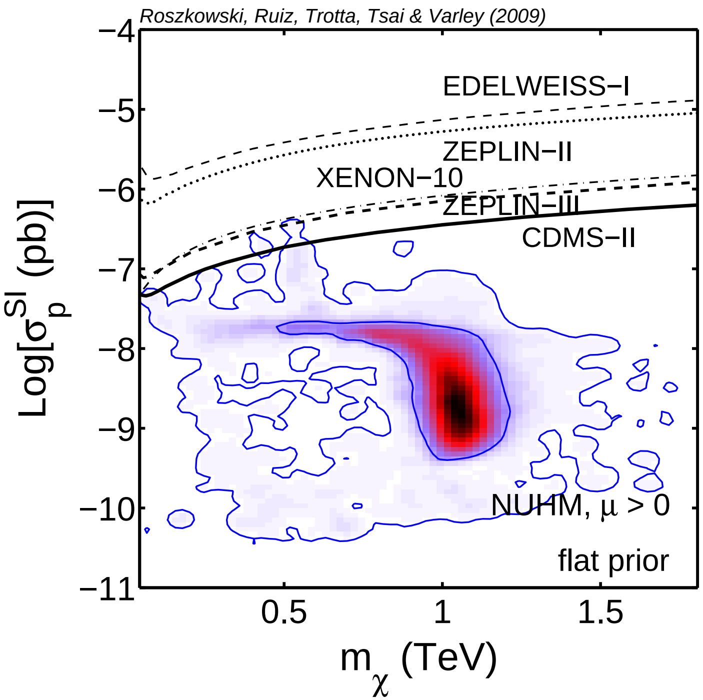

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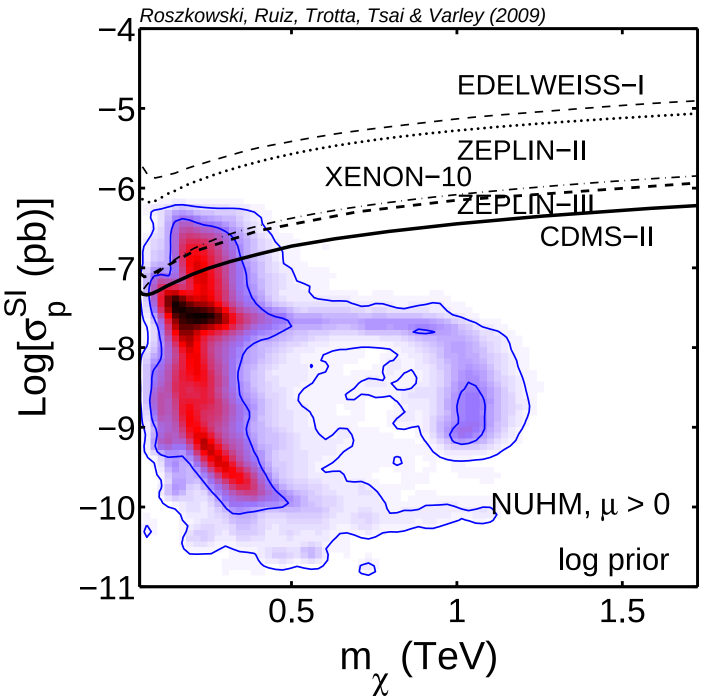

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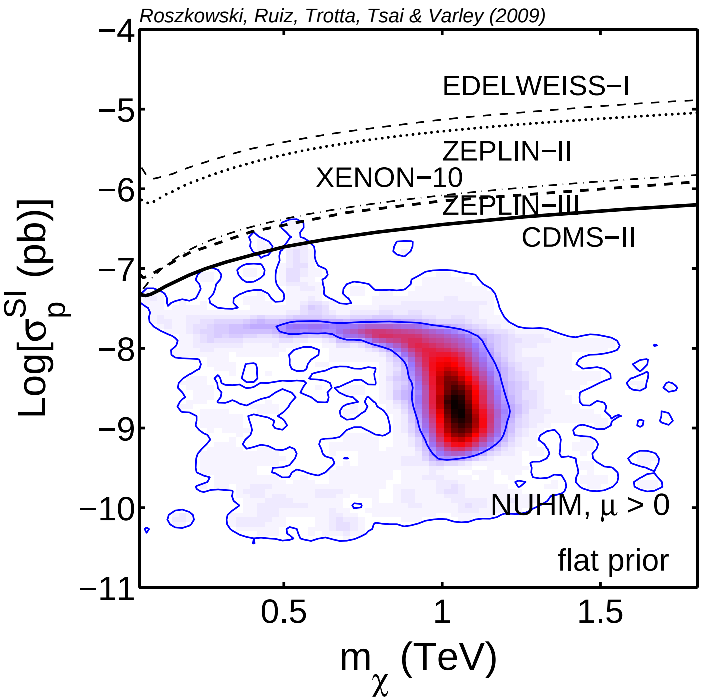

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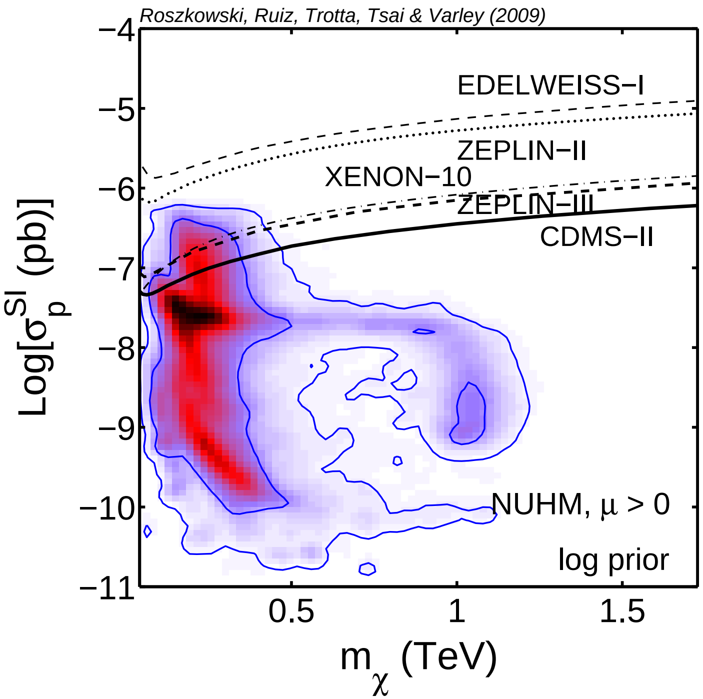

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$\Rightarrow$ NUHM: new higgsino LSP region at $m_\chi \sim 1\,\mathrm{TeV}$

$\Rightarrow$ large prior dependence

Indirect detection

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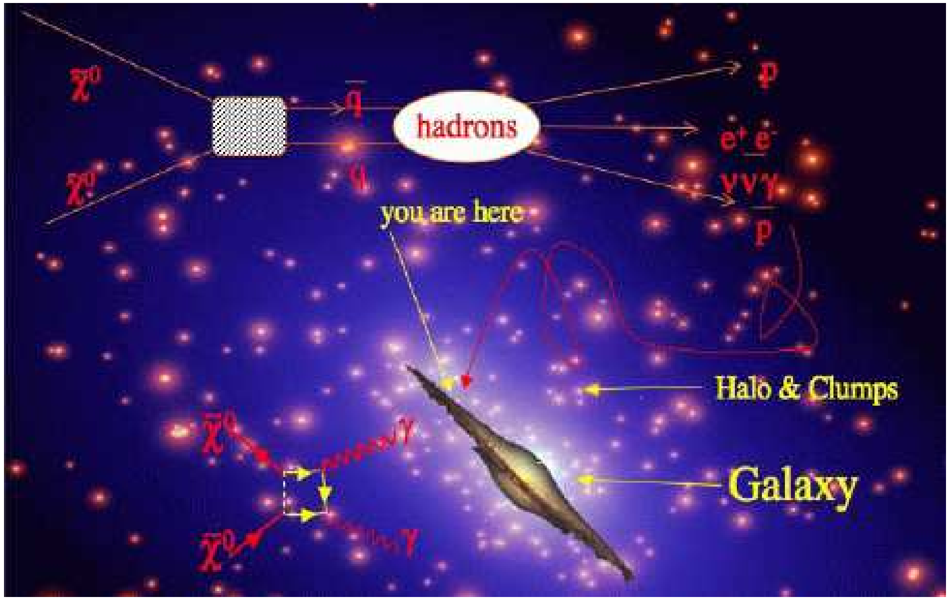

look for traces of WIMP annihilation in the MW halo

detection prospects often strongly depend on astrophysical uncertainties

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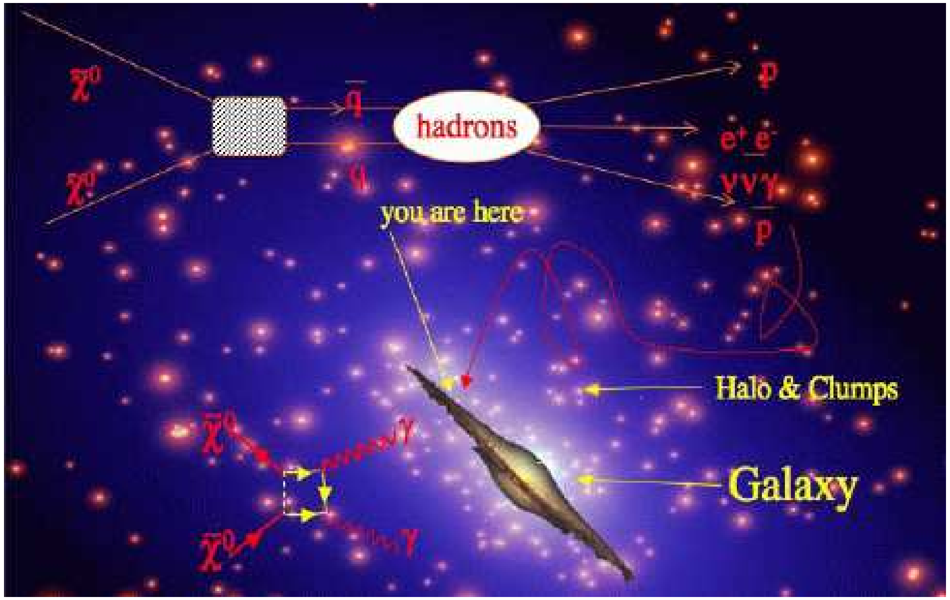

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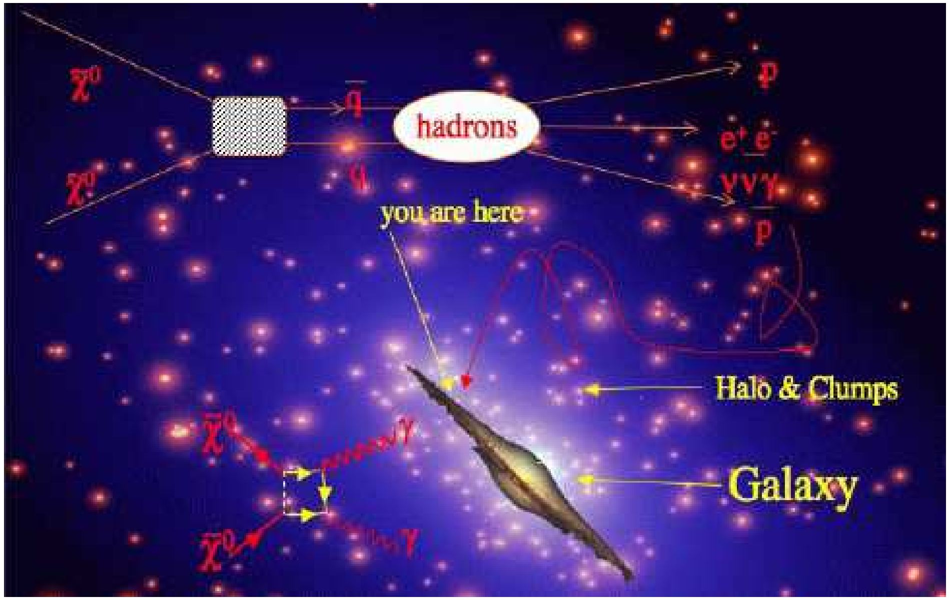

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- dark halo models?
- overdense regions (clumps)?
- DM density profile near Galactic center?

CDM Halo Models

...not a settled matter

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fitting DM halo with a semi-heuristic formula: ...not a settled matter

$$\rho_{DM}(r) = \rho_c / \left(\frac{r}{a}\right)^{\gamma} \left[1 + \left(\frac{r}{a}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}$$

α, β, γ - adjustable parameters

$\rho_c = \rho_0 \left(\frac{r_0}{a}\right)^{\gamma} \left[1 + \left(\frac{R_0}{a}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}$, $\rho_0 \sim 0.3\,\mathrm{GeV}/\,\mathrm{cm}^3$ - DM density at r_0

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some most popular models:

halo model	a (kpc)	r_0 (kpc)	(α, β, γ)	small r $r \propto r^{-\gamma}$	large r $r \propto r^{-\beta}$
isothermal cored	3.5	8.5	$(2, 2, 0)$	flat	r^{-2}
NFW	20.0	8.0	$(1, 3, 1)$	r^{-1}	r^{-3}
NFW-c	20.0	8.0	$(1.5, 3, 1.5)$	$r^{-1.5}$	r^{-3}
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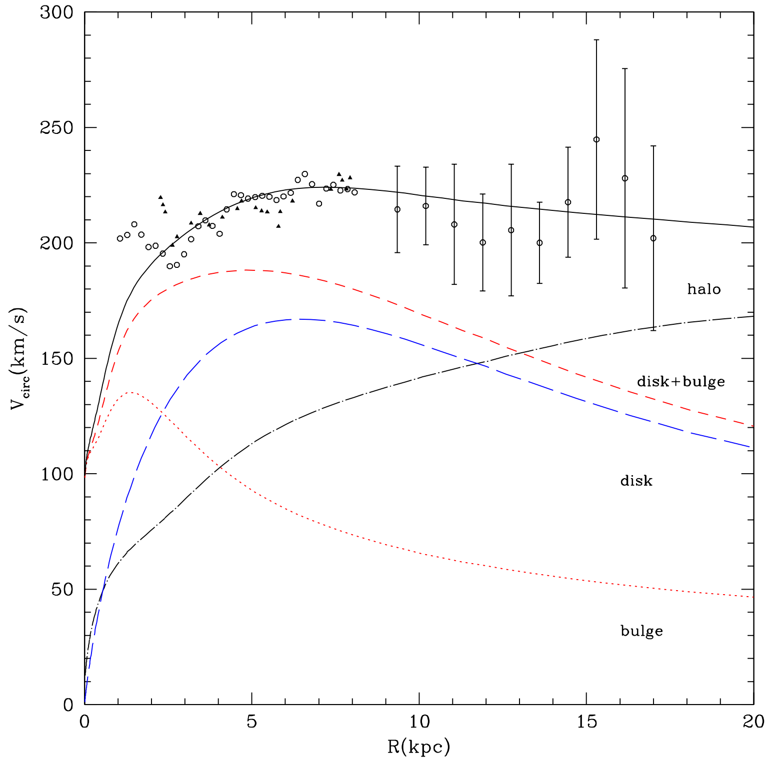
Many open questions: clumps??, central cusp??, spherical or tri–axial??,...

Our Milky Way

example of a reasonable model



(Klypin, et al., 2001)

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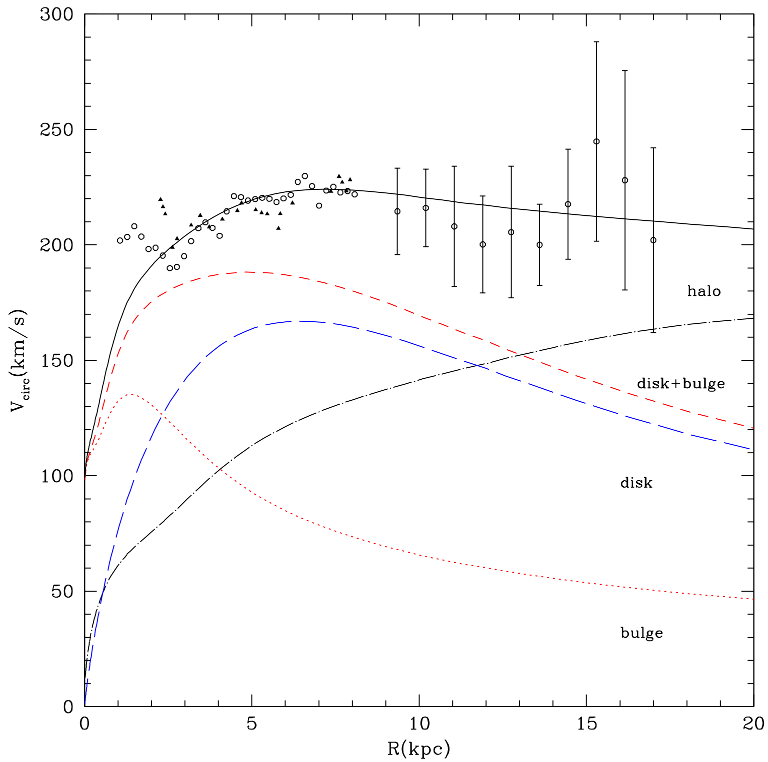
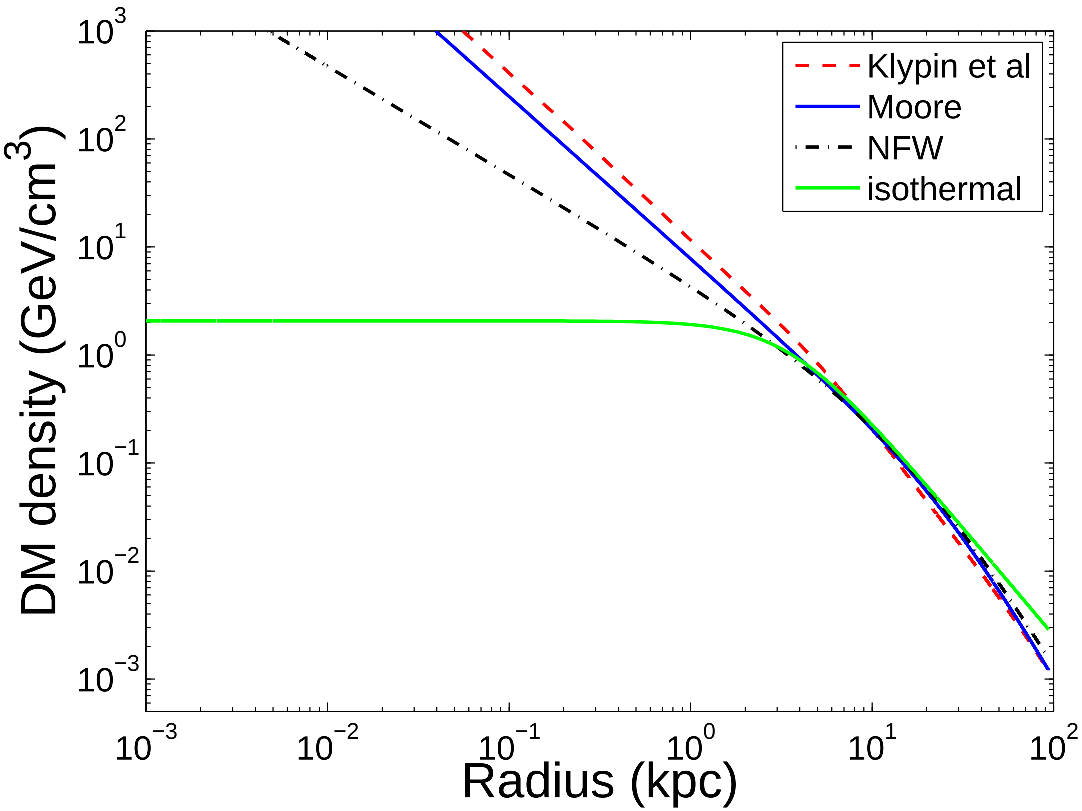


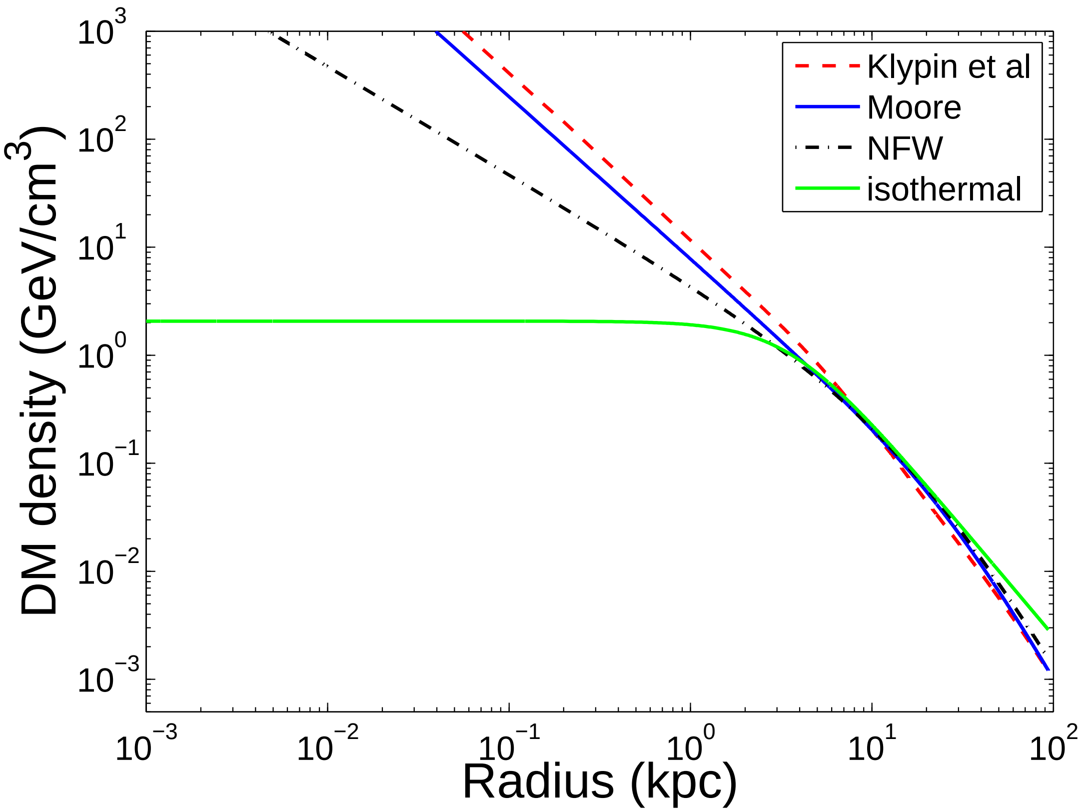
- based on NFW model with angular mom. exchange between baryons and DM
- DM dominates only at large r, well beyond the solar radius
- DM likely to be subdominant in the inner regions
- if no exchange of angular mom.: more DM in the center (but problem with fast rotating bar?)

Halo models



Klypin et al
Moore
NFW
isothermal
DM density (GeV/cm^3)
Radius (kpc)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

Halo models



- steeper inner profie $r^{-1.8}$ $\Rightarrow$ stronger DM annihilation at small r

Diffuse GRs from the GC

use Fermi/GLAST parameters

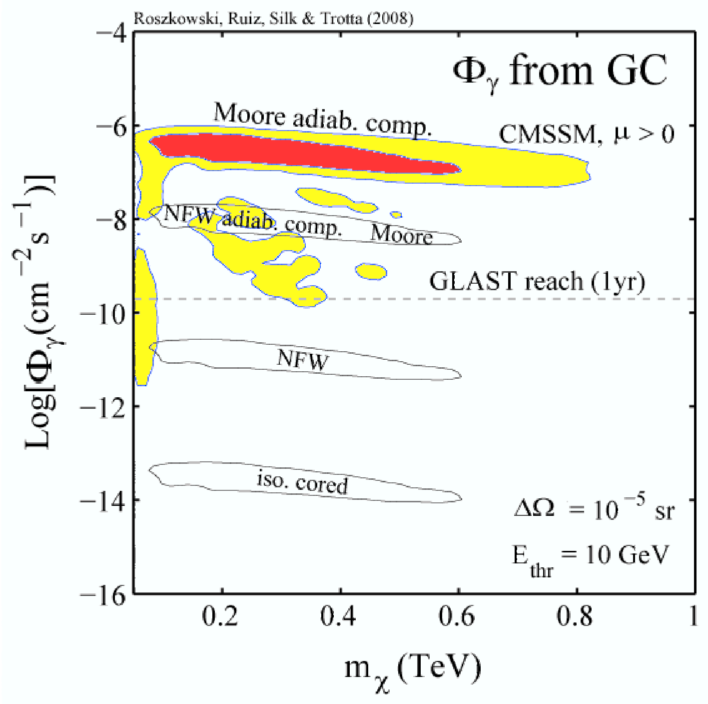
Bayesian posterior probability maps

Diffuse GRs from the GC

use Fermi/GLAST parameters

Bayesian posterior probability maps

CMSSM, flat priors



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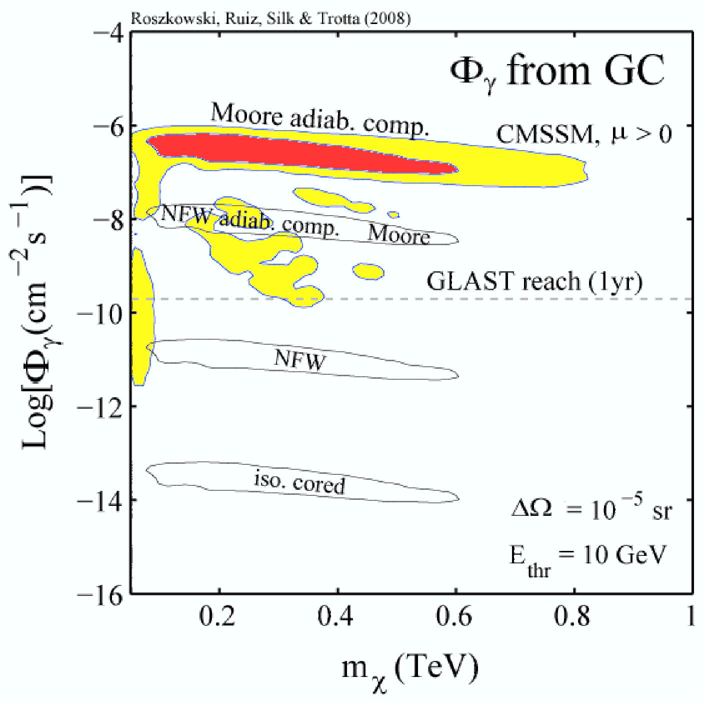
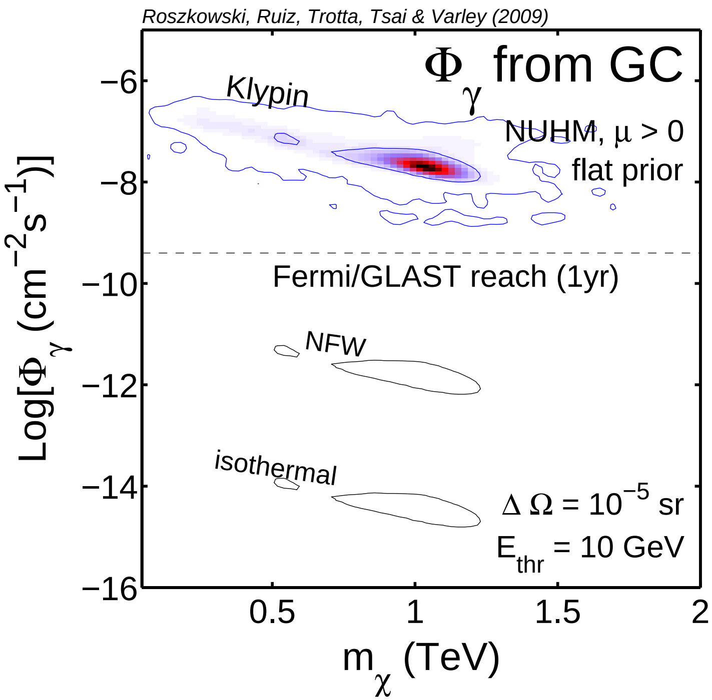


NUHM, flat priors



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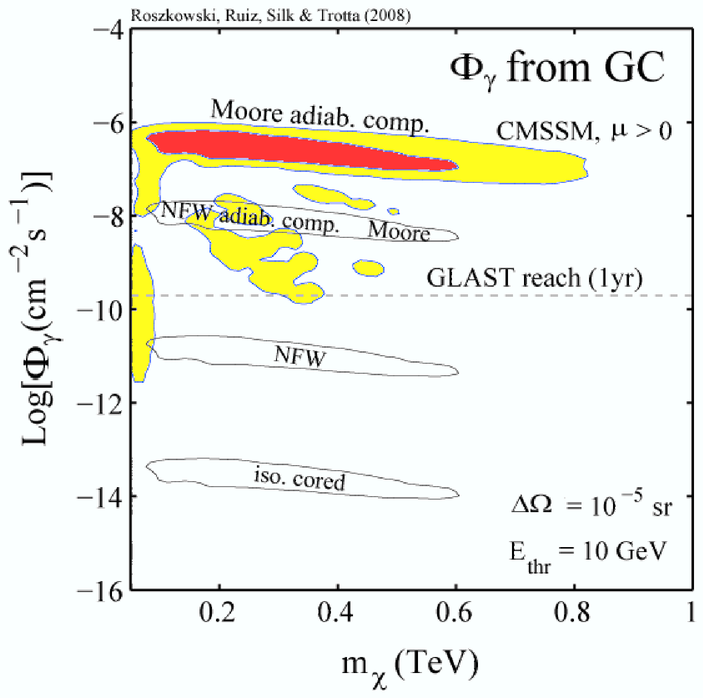

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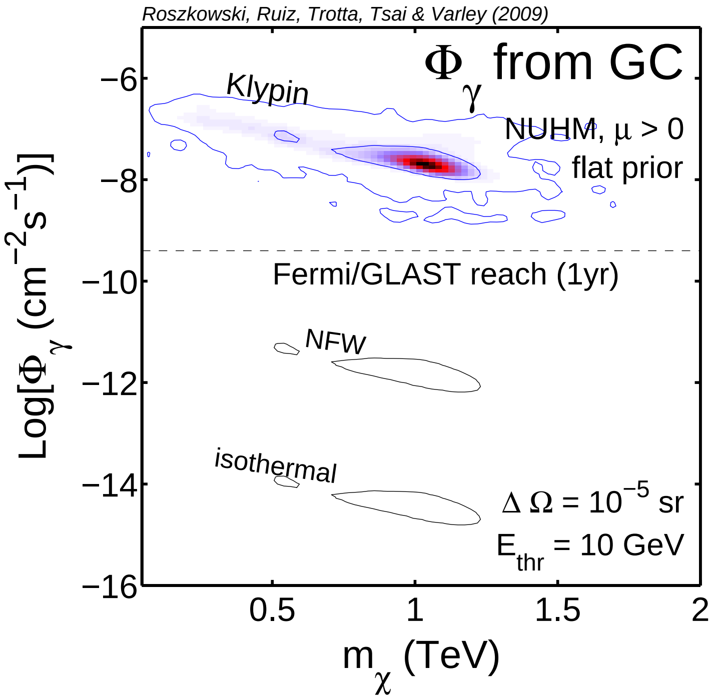

$\Rightarrow$ WIMP signal at Fermi/GLAST: outcome depends on halo cuspiness at GC

Impact of Priors

use Fermi/GLAST parameters

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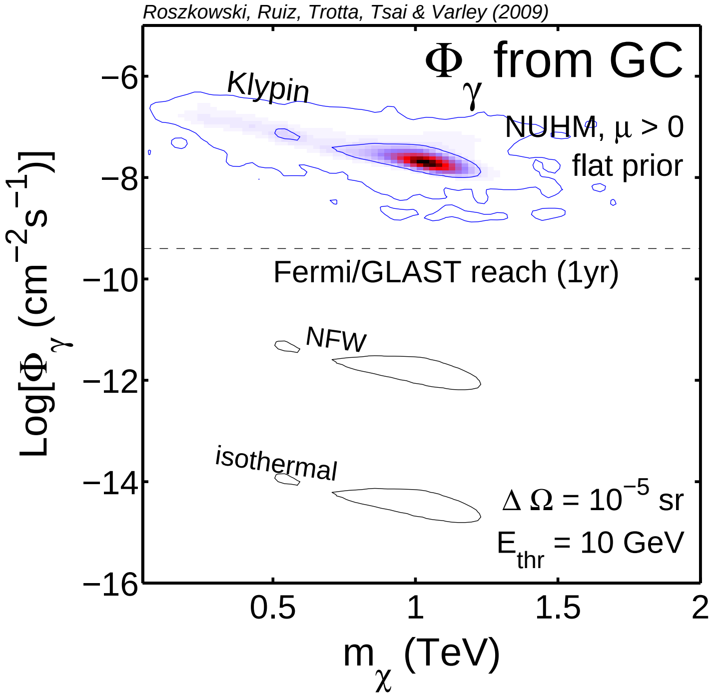

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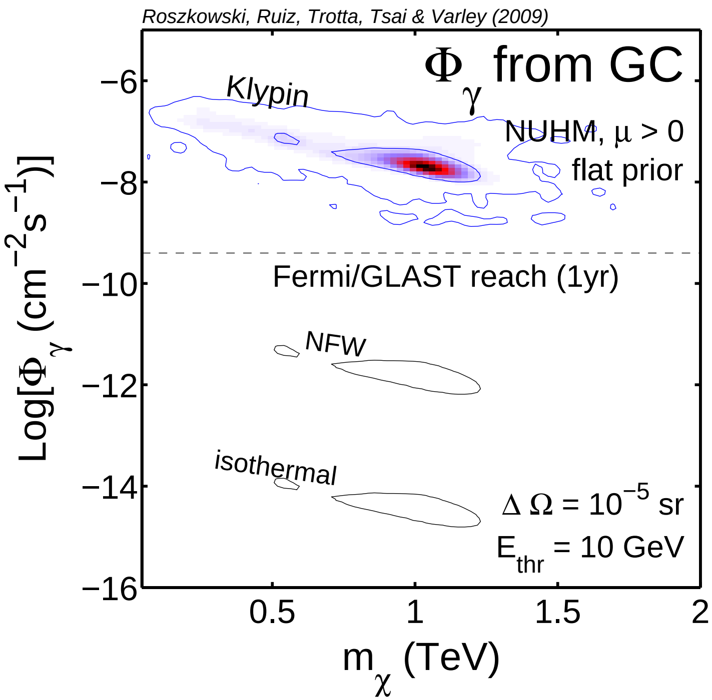
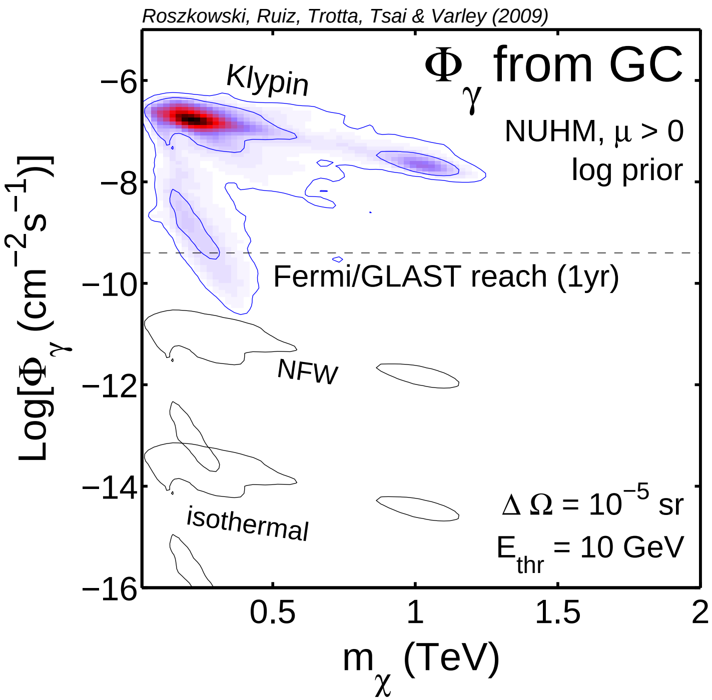


NUHM, log priors



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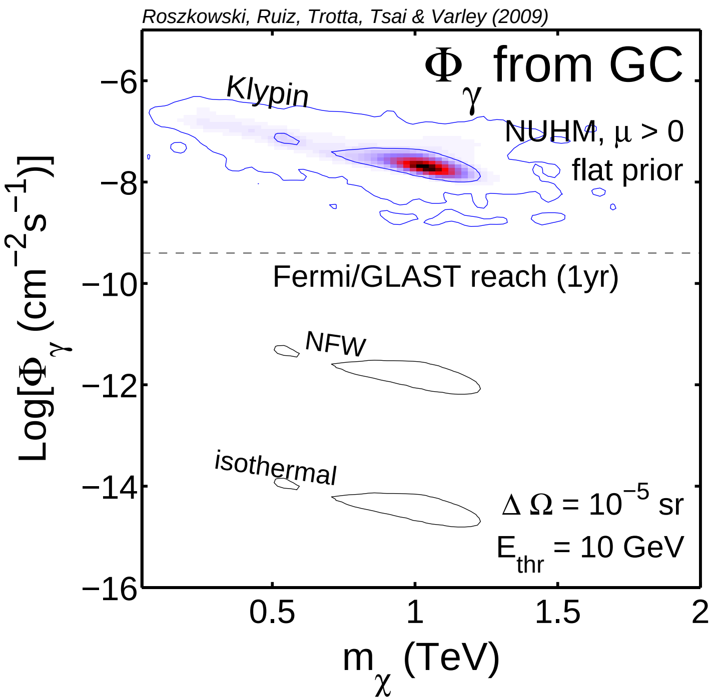

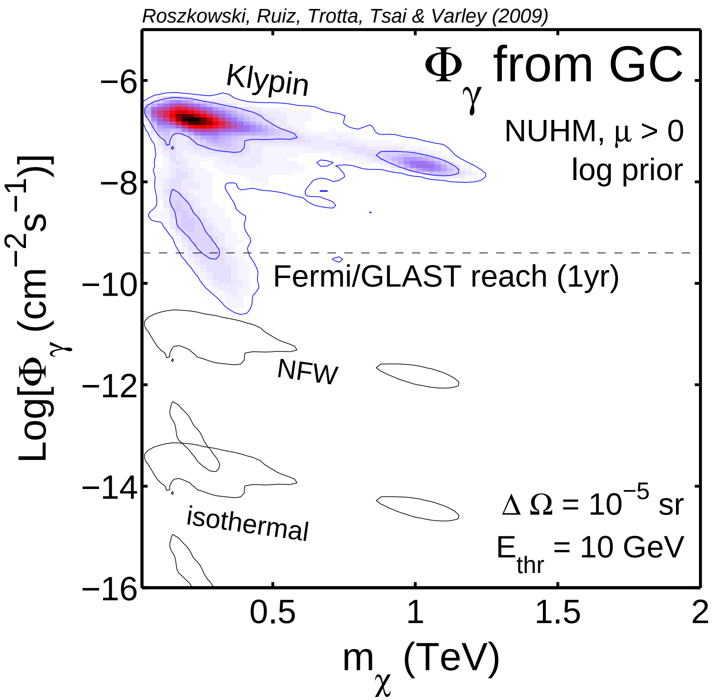

log prior:

$\Rightarrow$ sqeeze towards lower mass (as expected)

$\Rightarrow$ higher fluxes

e^+ data from PAMELA

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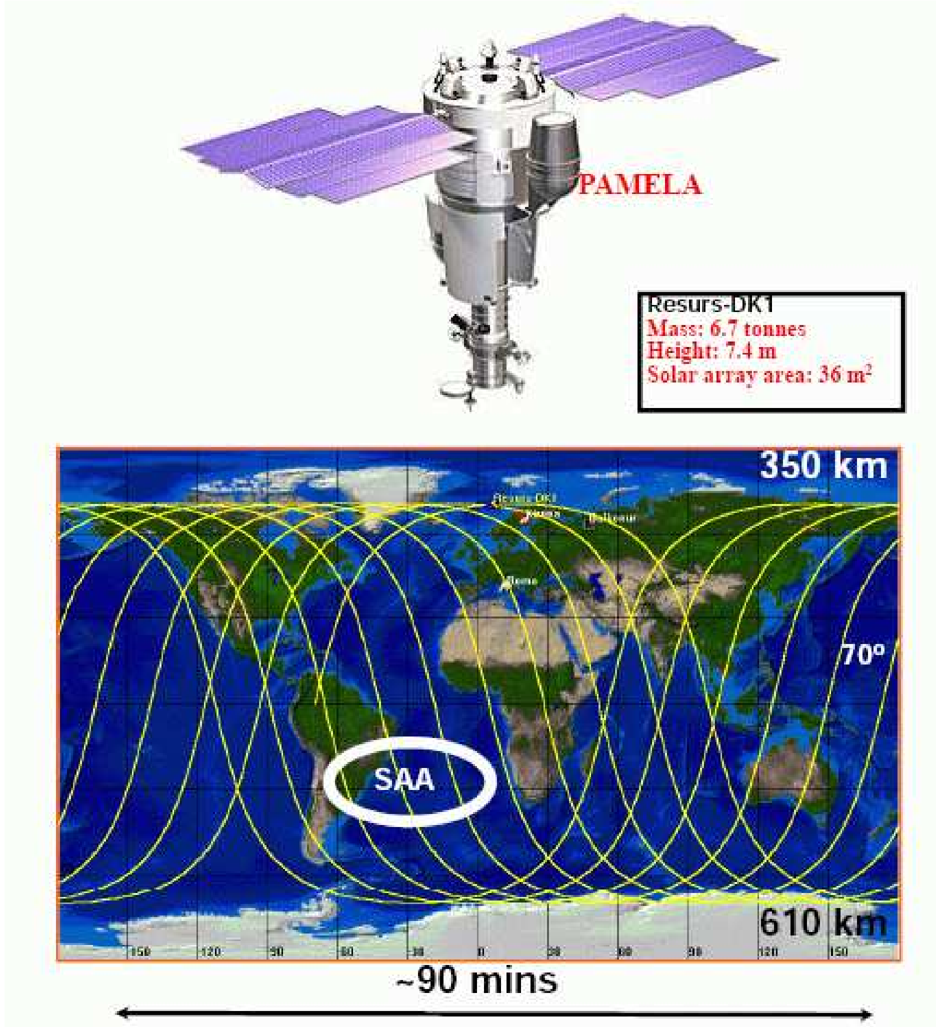
- PAMELA satelite (since 2007)



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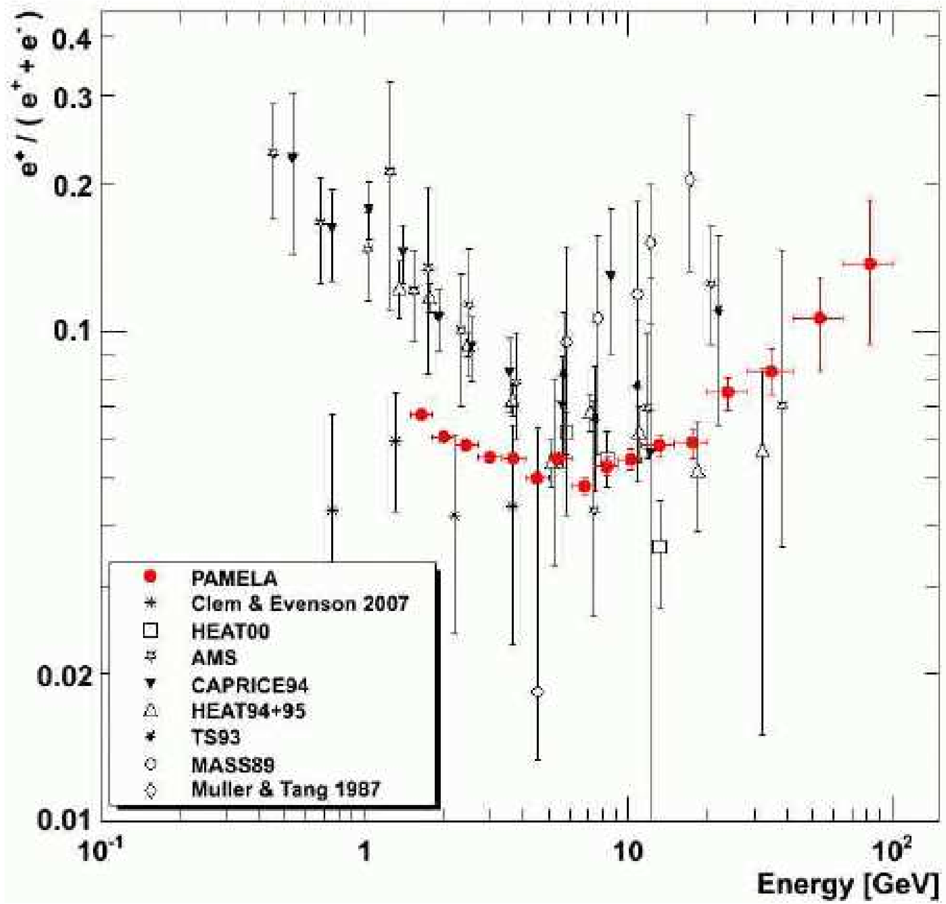

O. Adriani et al., arXiv:0810.4995

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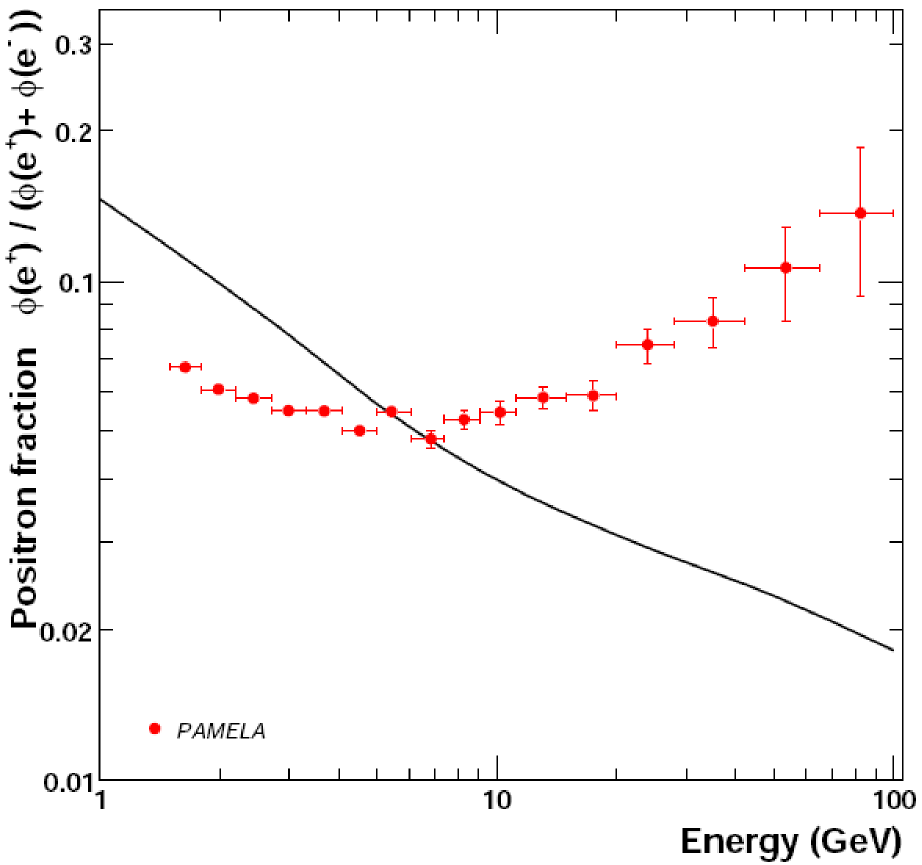

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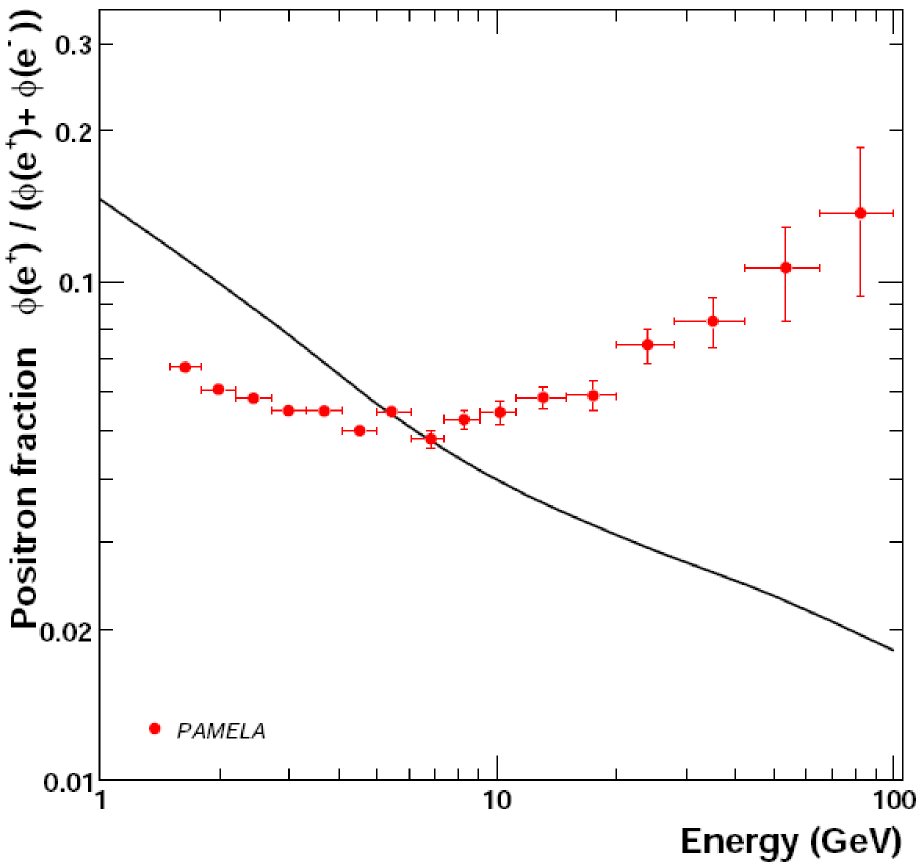

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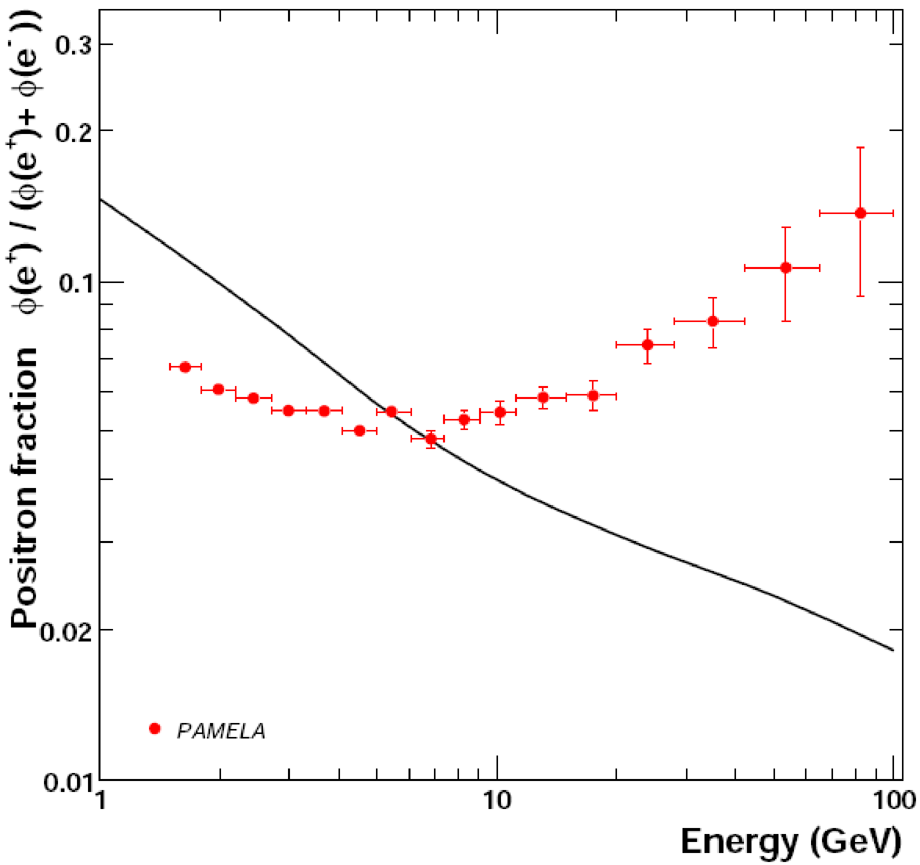

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...analysis to be cross-checked, result to be verified by AMS

Positron flux and PAMELA

Positron flux and PAMELA

- e^+'s from DM annihilations
- propagate in interstellar magnetic field

$$K(\epsilon) = 2.1 \times 10^{28} \epsilon^{0.6}\,\mathrm{cm}^2\,\mathrm{sec}^{-1}$$

$$\epsilon = E_{e^+}/1\,\mathrm{GeV}$$

- much less dependence on halo model
- loose energy via inverse Compton scattering

$$b(\epsilon) = \frac{\epsilon^2}{\tau_E} \approx 10^{-16} \epsilon^2\,\mathrm{sec}^{-1}$$

$$\tau_E = 10^{16}\,\mathrm{sec}^{-1}$$

- diffusion zone:
  infinite slab of height $L = 4$ kpc, free escape BC's

SUSY: Positron flux

Bayesian posterior probability maps

BF=1

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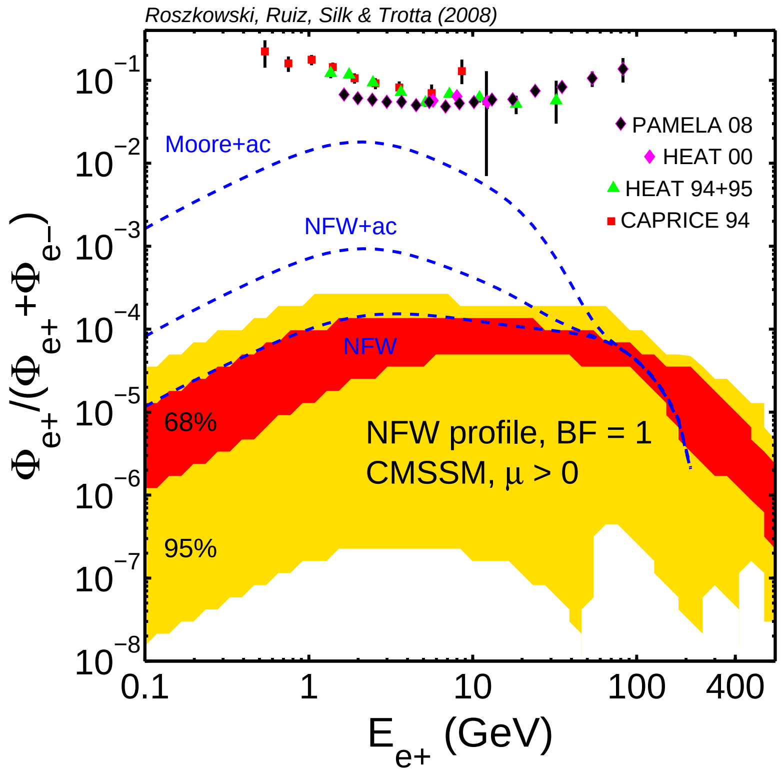
CMSSM, flat priors, NFW



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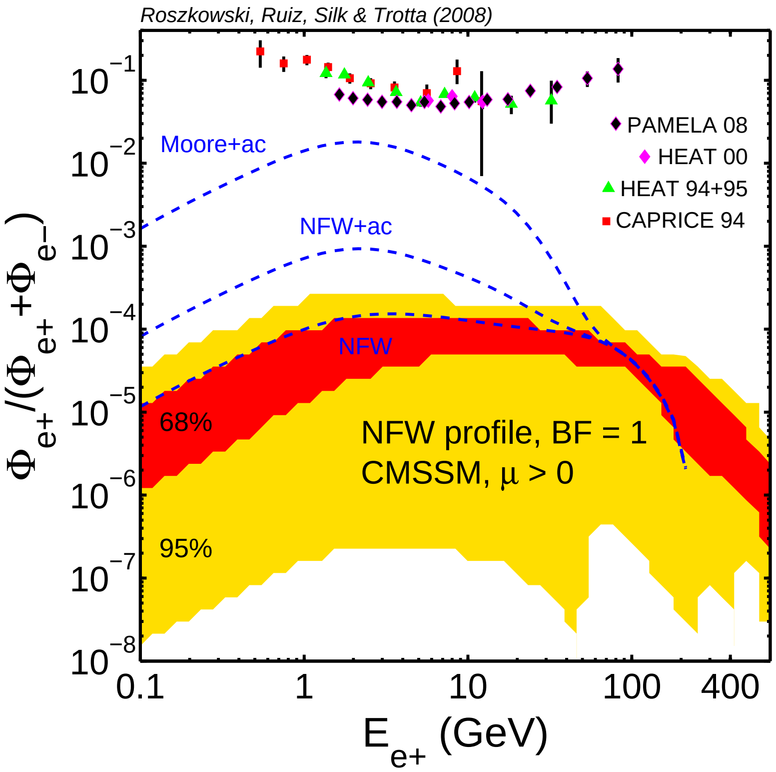

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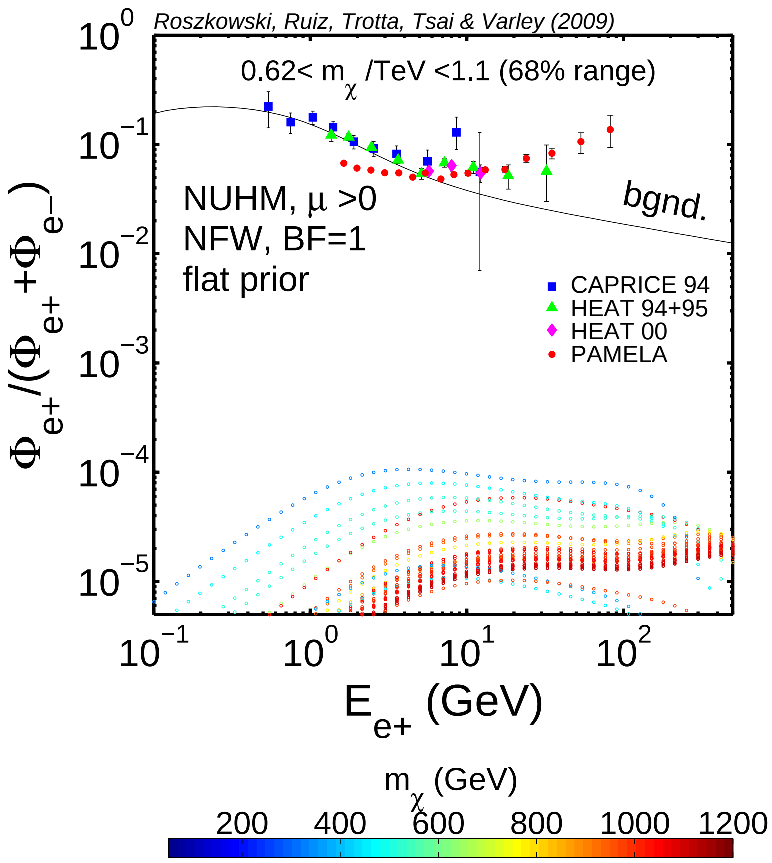

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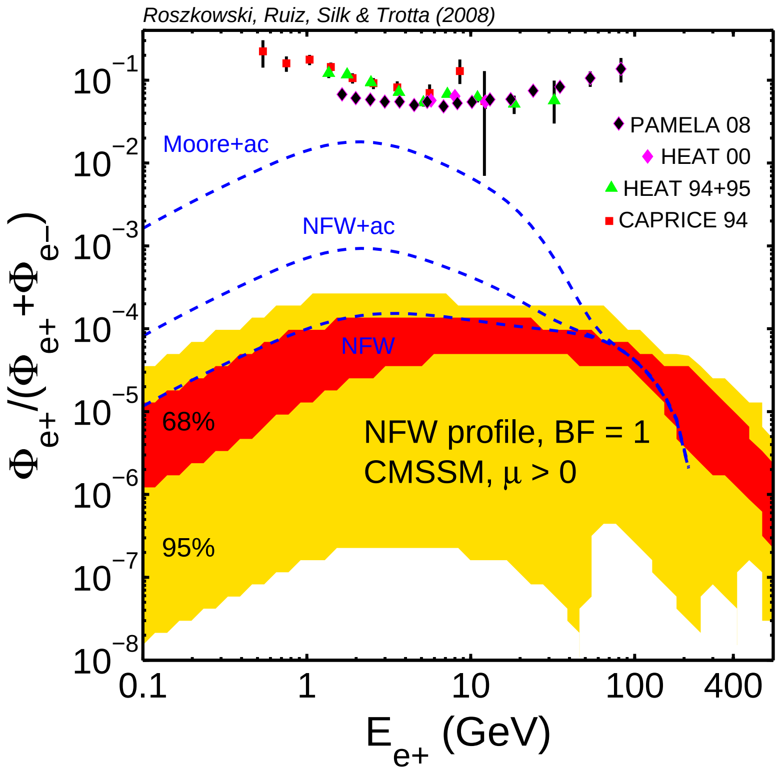

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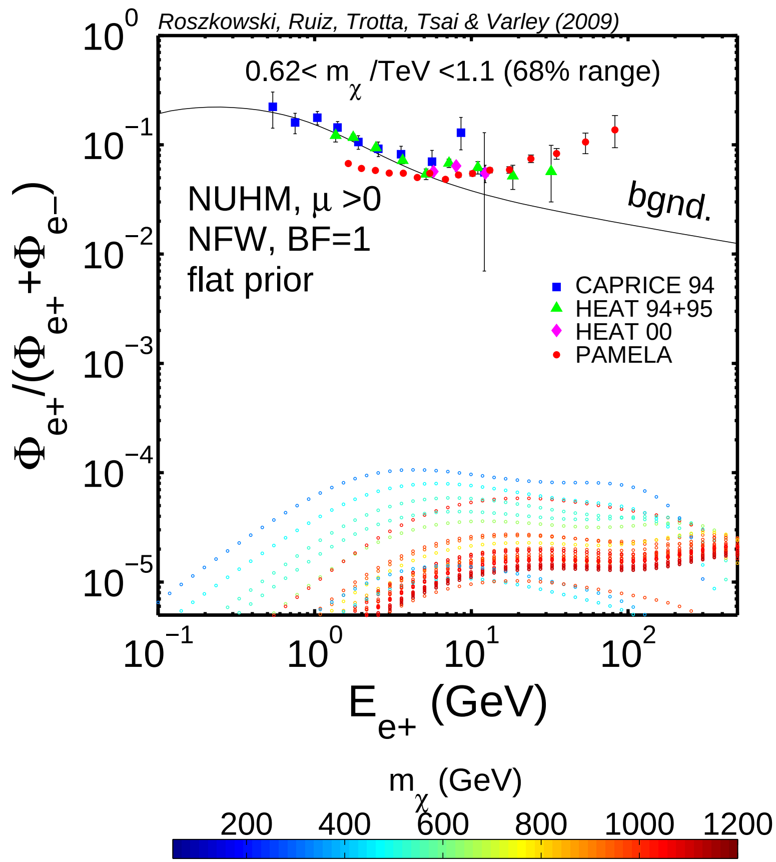

⇒ CMSSM, NUHM: inconsistent with PAMELA e^+ claim

...even for unrealistically large boost factors

(flux scales linearly with boost factor)

The great tragedy of Science – the slying of a beautiful hypothesis by an ugly fact

T.H. Huxley

One should never believe any experiment until it has been confirmed by theory

A. Eddington

Summary

- unified SUSY models remain by far most attractive and well-motivated candidates for “new physics”
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- PAMELA e^+ result inconsistent with neutralino DM in unified SUSY

  ...astrophysical explanation (pulsars)?

  ...proton rejection poorer than assumed?

when looking for truth...

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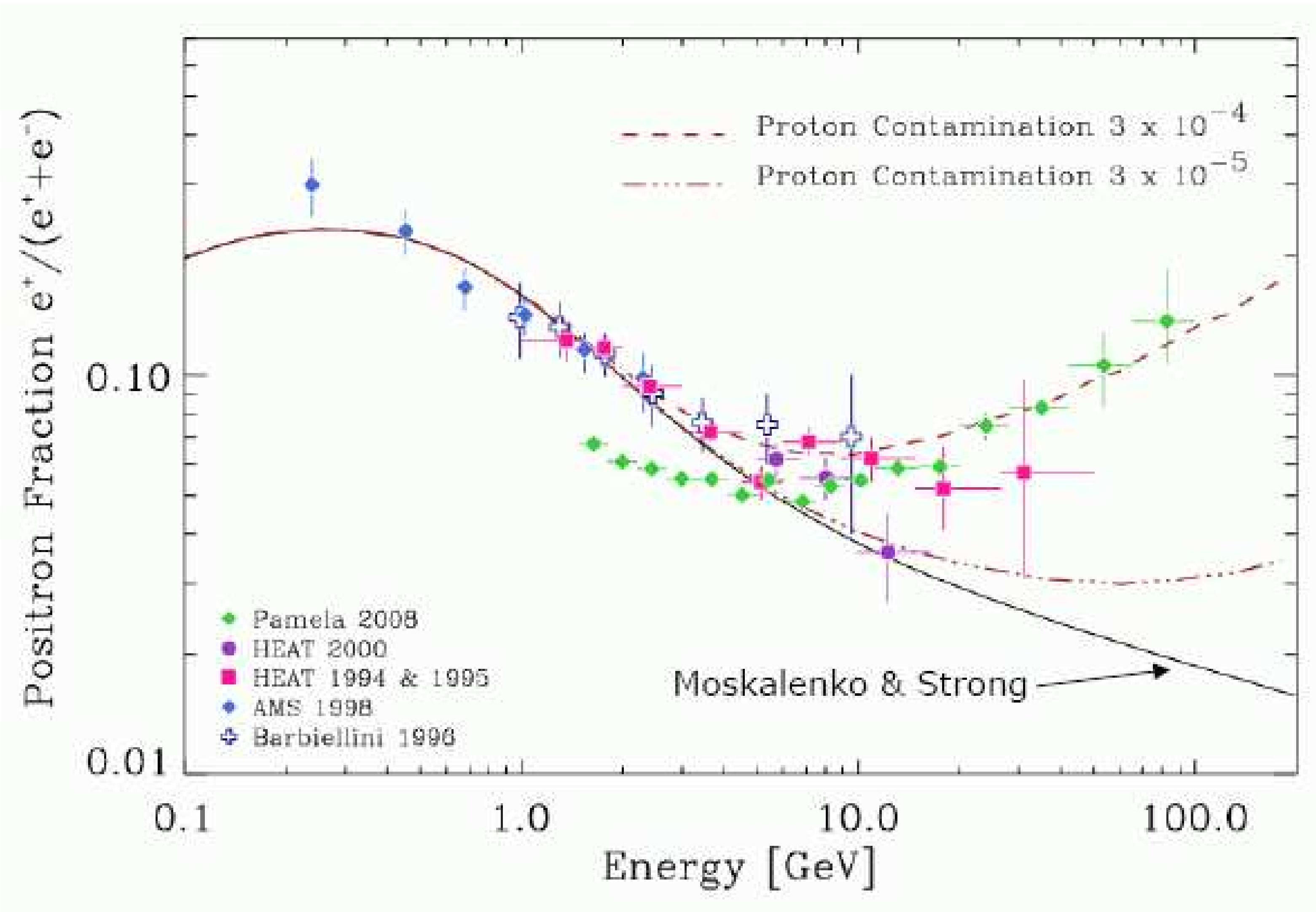
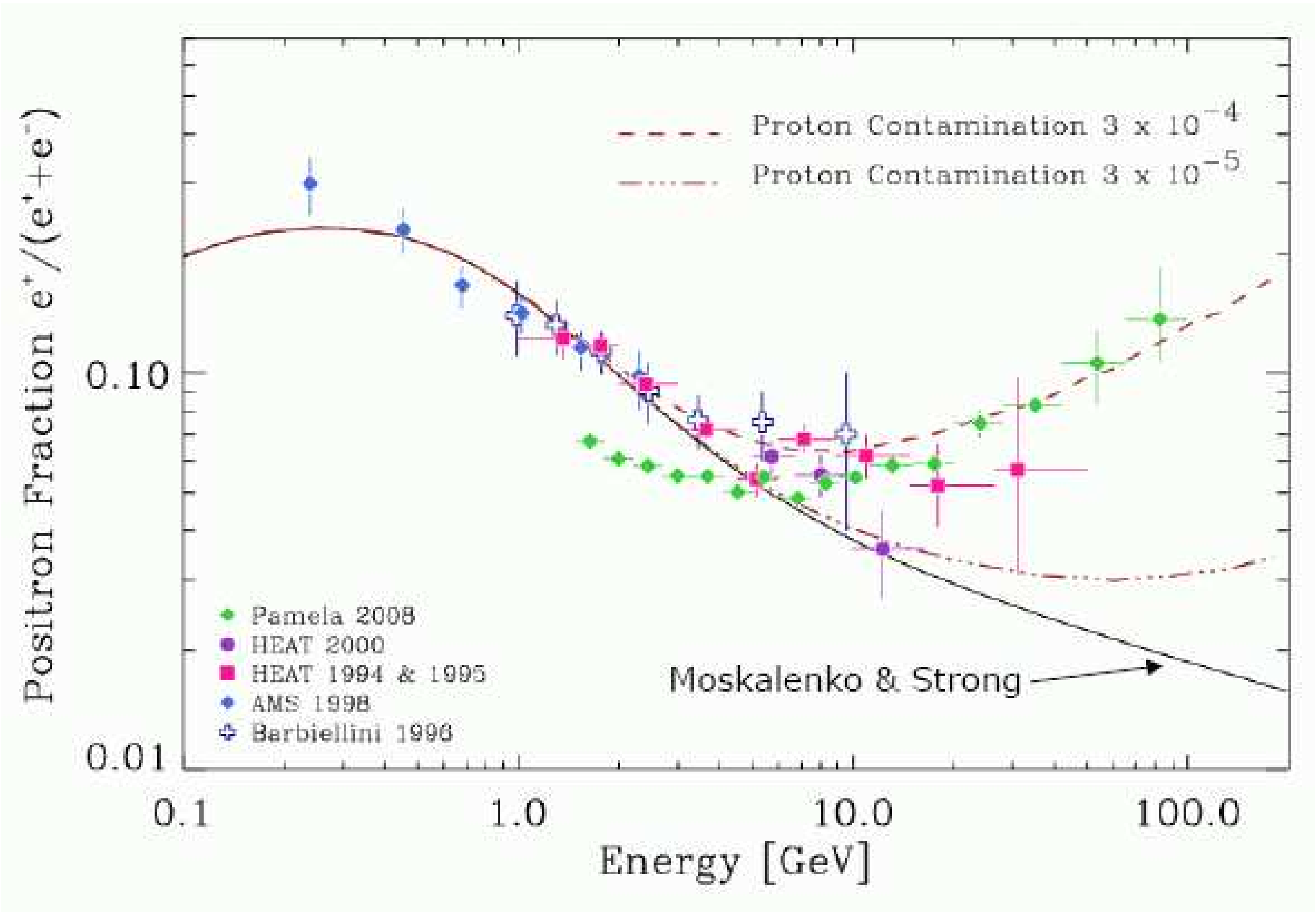
look no further than (Bayesian) statistics

Backup...



Proton Contamination 3 x 10^-4
Proton Contamination 3 x 10^-5
Positron Fraction e+/(e++e-)
0.10
0.01
0.1
1.0
10.0
100.0
Energy [GeV]
Pamela 2008
HEAT 2000
HEAT 1994 & 1995
AMS 1998
Barbiellini 1996
Moskalenko & Strong

M. Schubnell



M. Schubnell

- Pamela e^+ excess consistent with mis-identifying 3 in 10,000 protons as positrons