Dark Matter and Bayesian Approach to SUSY Models

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Outline

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- DM candidates and particle physics models

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- SUSY neutralino - most popular candidate

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- summary

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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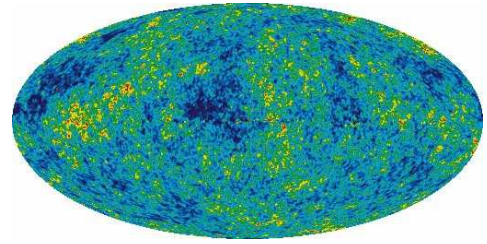
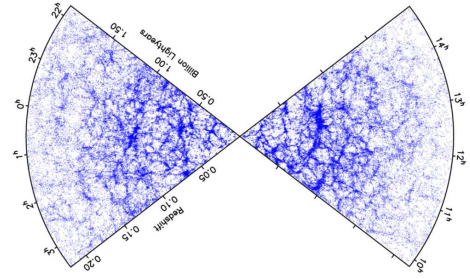
assume simplest ΛCDM model

- 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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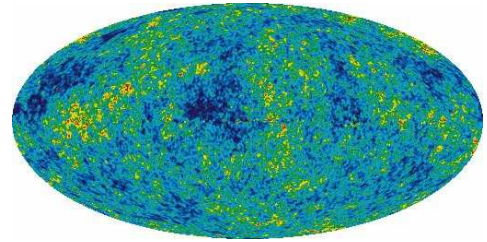

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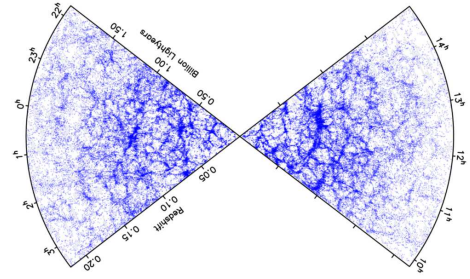

- concordance model works well
- main components: dark energy and dark matter

factor of 4-10 improvement expected from Planck

And the answer is...

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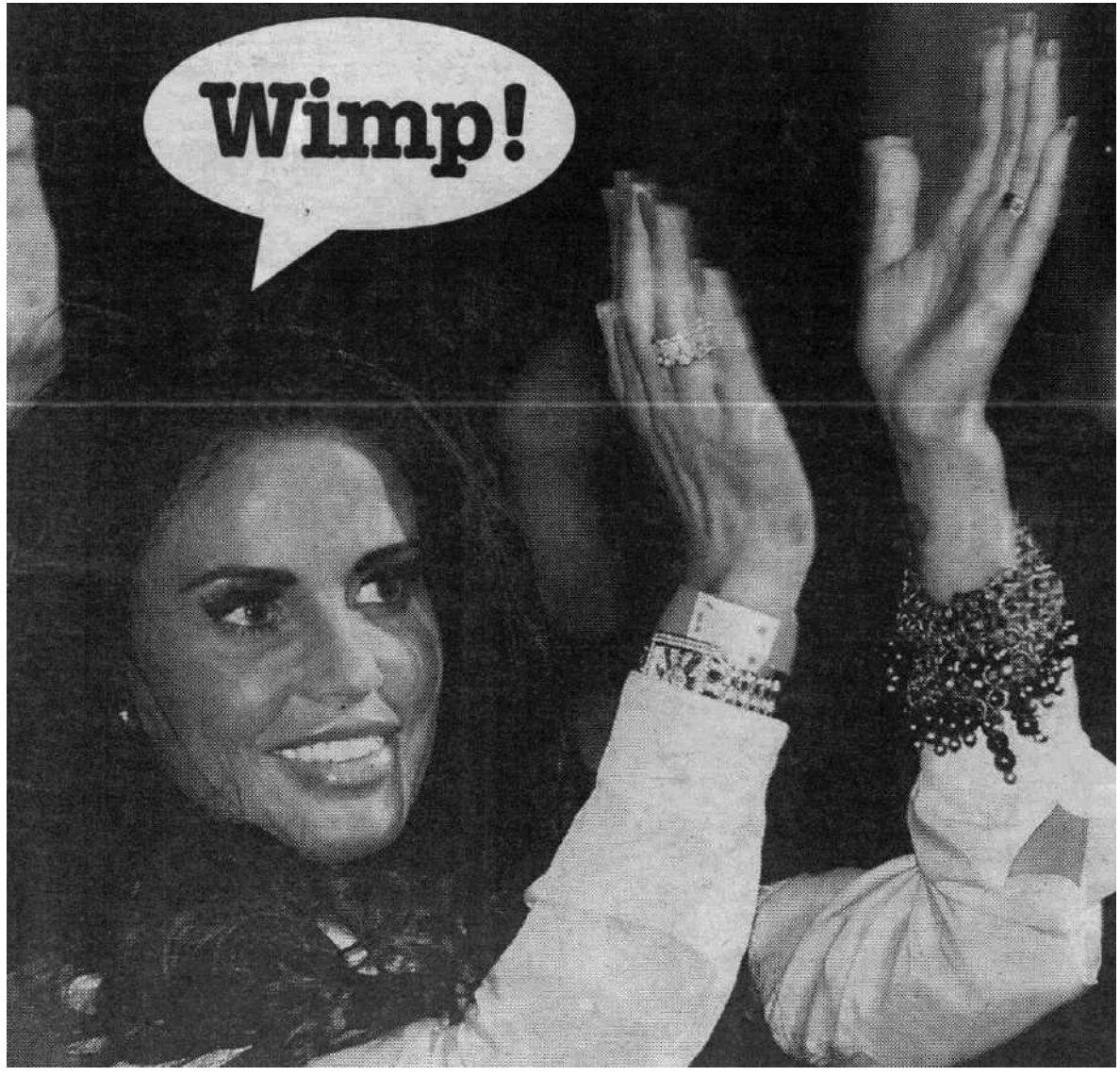


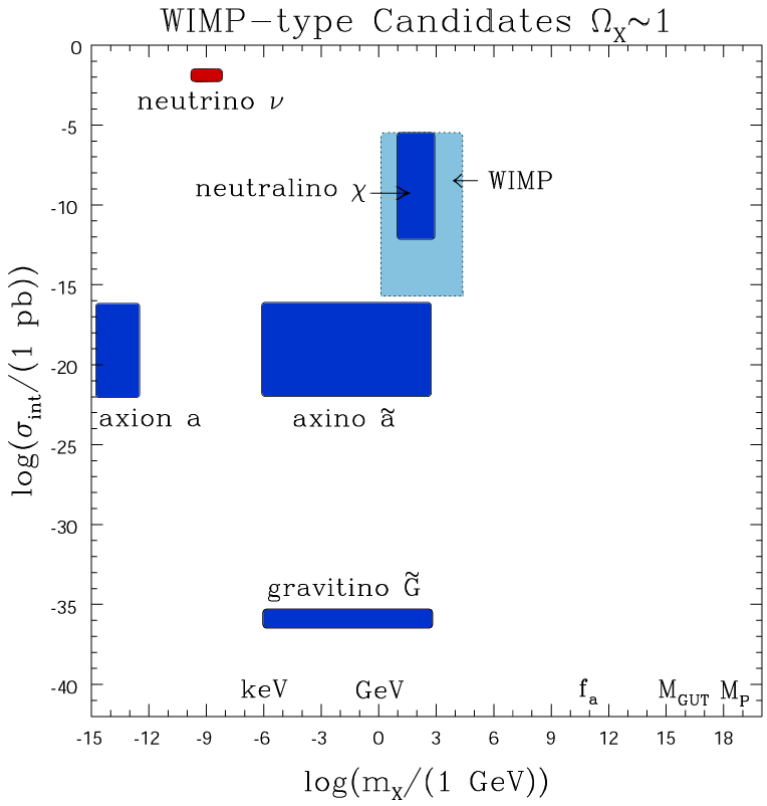
DM: The Big Picture

* – not invented to solve the DM problem

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

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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neutralino χ = lightest mass eigenstate
of neutral gauginos $\widetilde{B}$ (bino), $\widetilde{W_3^0}$ (wino) and neutral higgsinos $\widetilde{H_t^0}$, $\widetilde{H_b^0}$
Majorana fermion ($\chi^c = \chi$)

most popular candidate

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- part of a well-defined and well-motivated framework of SUSY
- 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)
- testable with today's experiments (DD, ID, LHC)
- ...no obviously superior competitor (both to SUSY and to χ) exists

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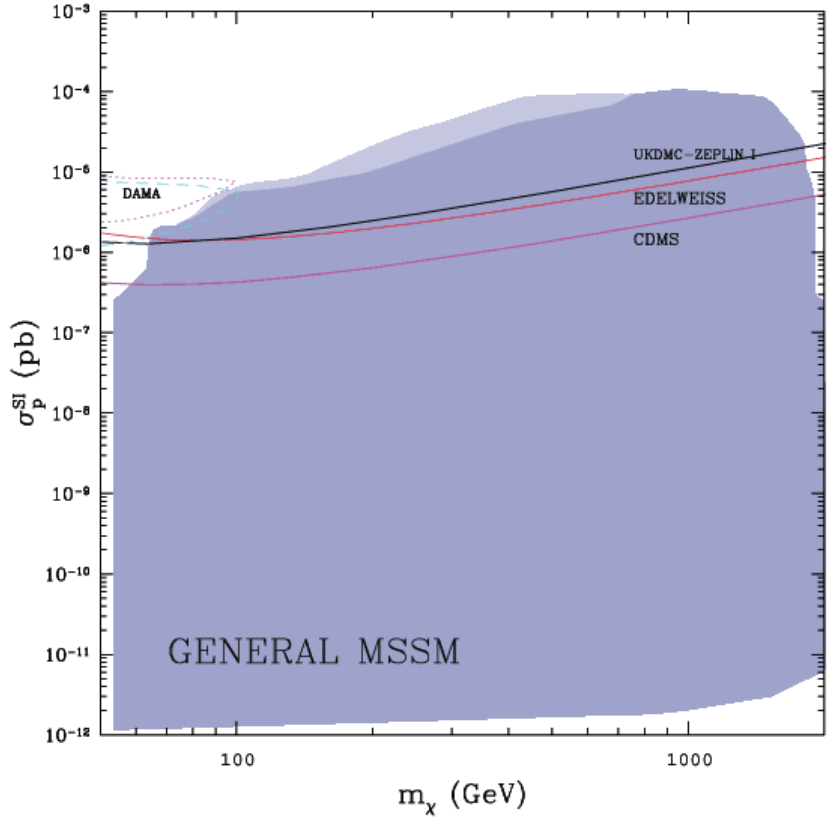
neutralino = stable, weakly interacting, massive $\Rightarrow$ WIMP

MSSM: Expectations for $\sigma_p^{\rm SI}$

general MSSM

$\mu > 0$

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



$\sigma_p^{\rm SI}$– WIMP–proton SI elastic scatt. c.s.

(elastic c.s. for $\chi p \longrightarrow \chi p$ at zero momentum transfer)

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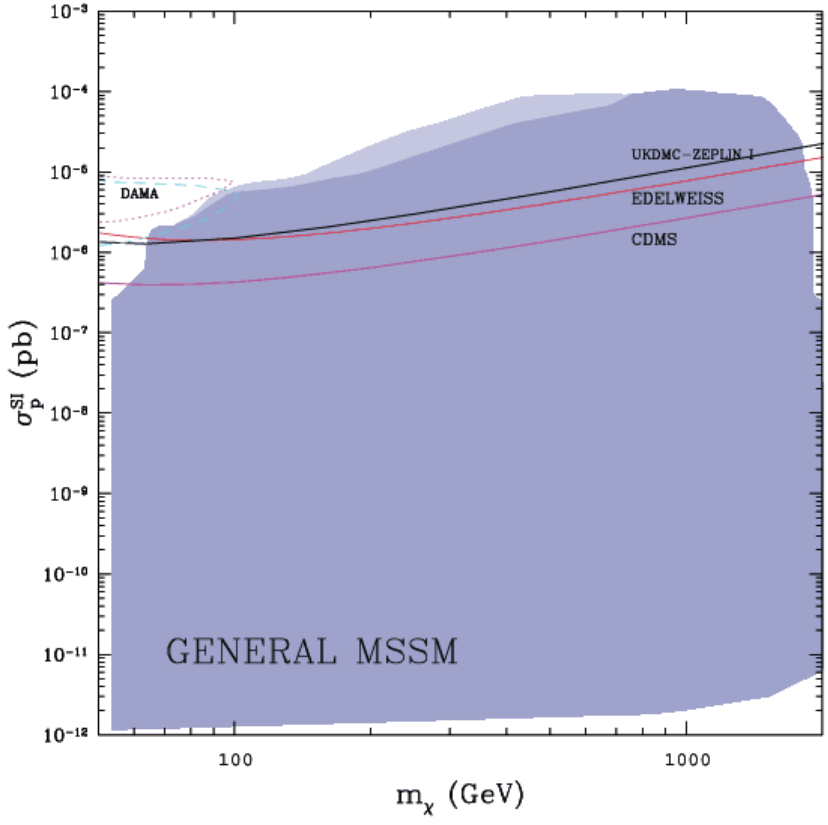

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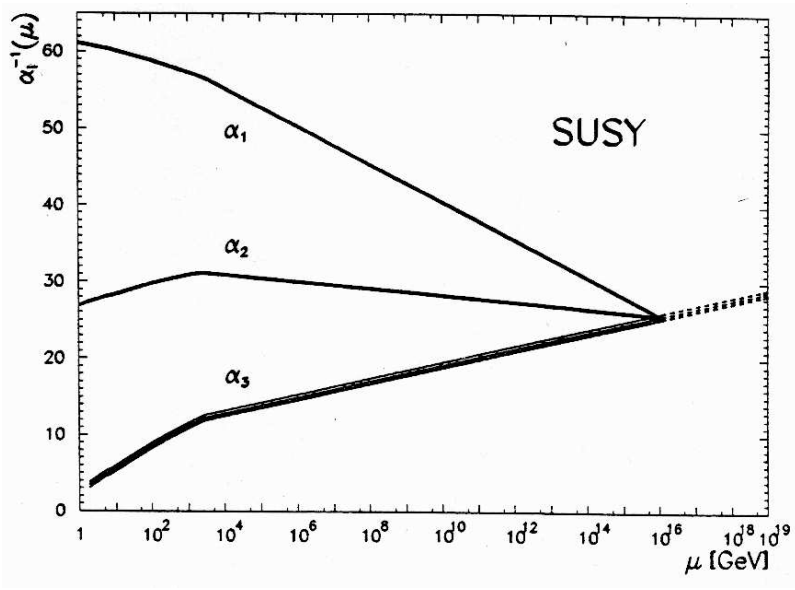
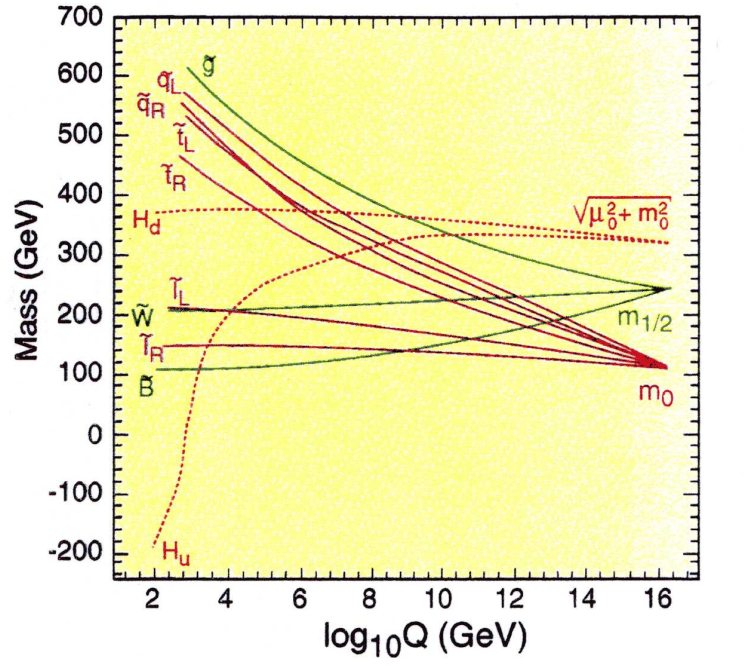
$\Rightarrow$ MSSM: vast ranges! Lacks real predictive power!

Add grand unification...



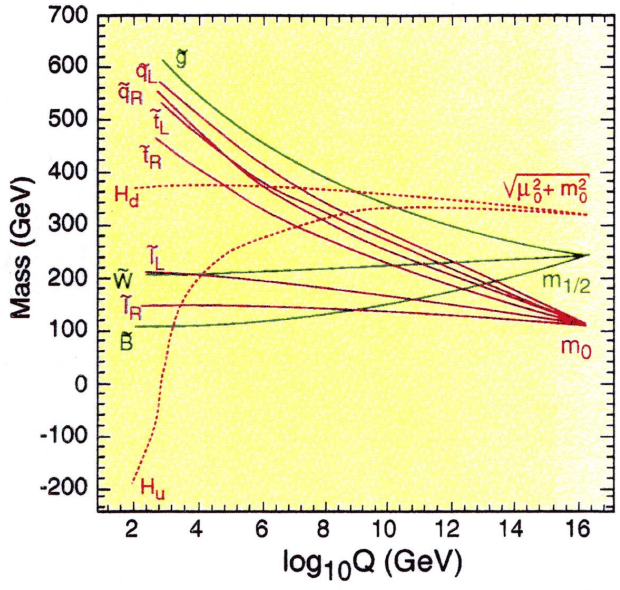


Constrained MSSM (CMSSM)

Kane, Kolda, LR, Wells (1993)

...“benchmark framework” for the LHC

(...e.g., mSUGRA)



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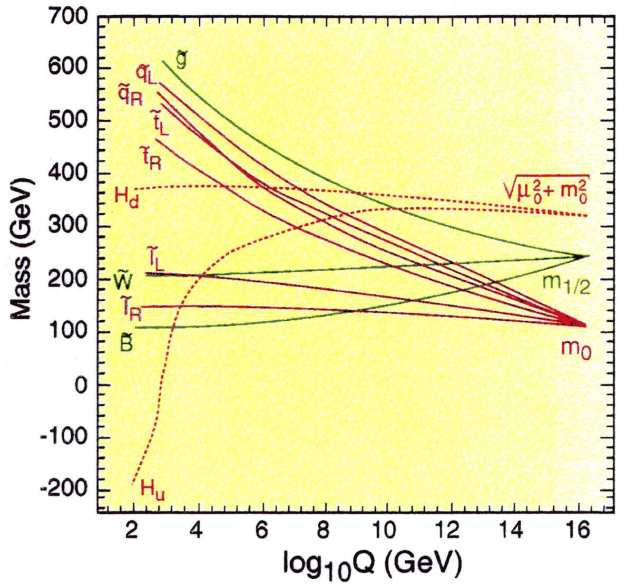

At $M_{\rm GUT} \simeq 2 \times 10^{16}\,{\rm GeV}$:

- gauginos $M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$
- scalars $m^2_{\tilde{q}_i} = m^2_{\tilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m_0^2$
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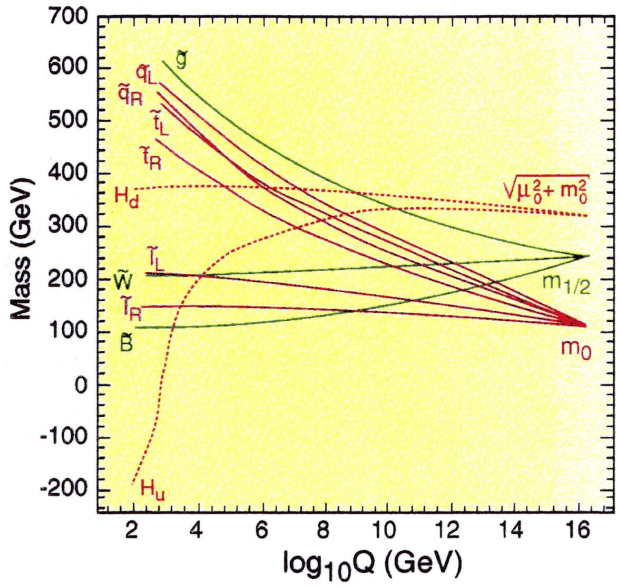

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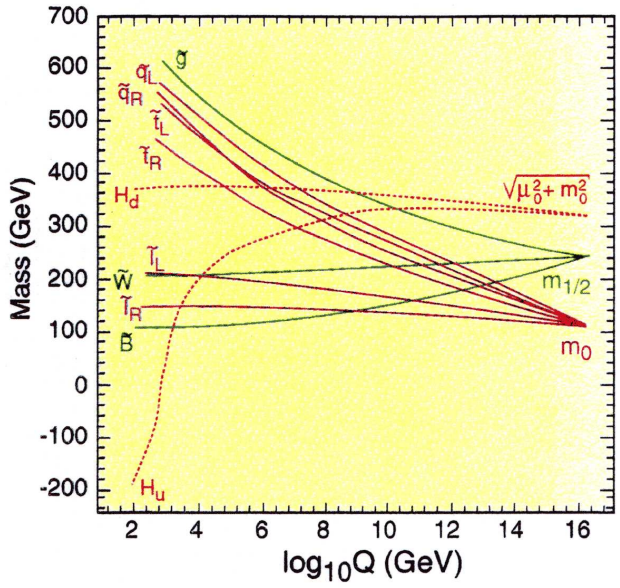

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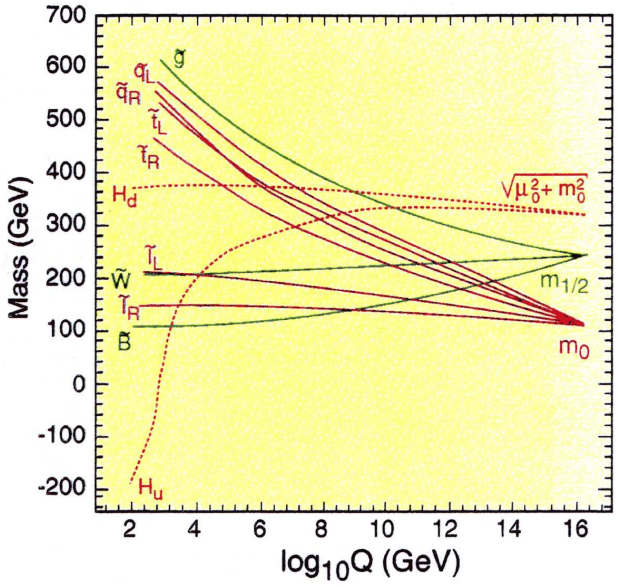

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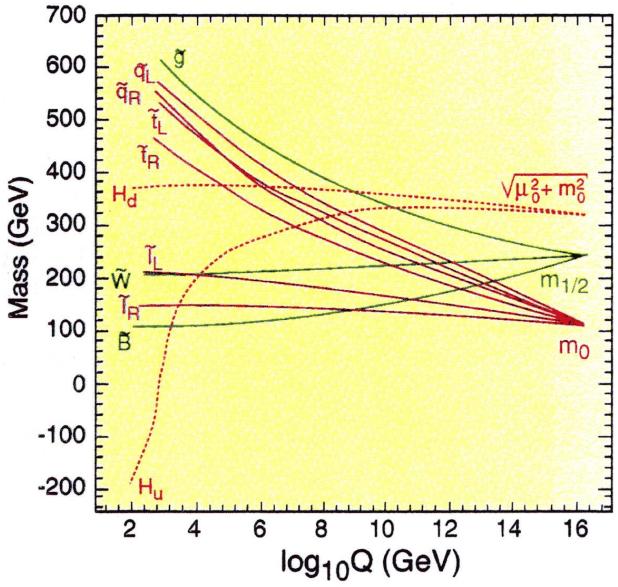

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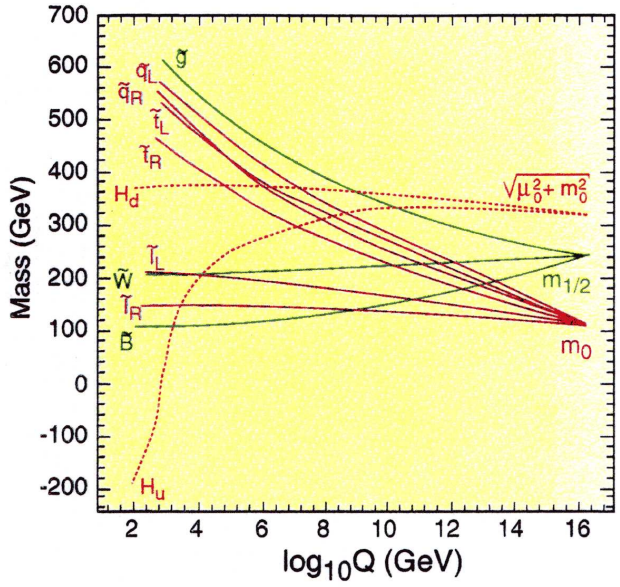

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some useful mass relations:

- bino: $m_\chi \simeq 0.4 m_{1/2}$
- gluino $\tilde{g}$: $m_{\tilde{g}} \simeq 2.7 m_{1/2}$
- supersymmetric tau (stau) $\tilde{\tau}_1$: $m_{\tilde{\tau}_1} \simeq \sqrt{0.15 m^2_{1/2} + m^2_0}$

Earlier analyses of CMSSM

very many papers

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Until recently usual approach has been to:

- do fixed-grid scans of $m_{1/2}$ and m_0 for fixed $\tan\beta$ and A_0
- apply constraints from LEP, $\mathrm{BR}(\bar{B} \to X_s\gamma)$, $\Omega_\chi h^2$, EWSB, charged LSP, etc
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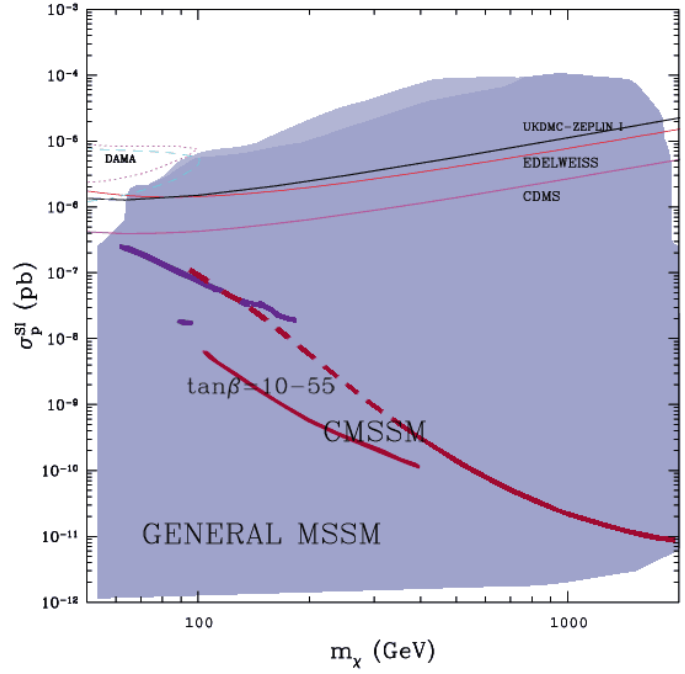
hep-ph/0404052



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Shortcomings:

- 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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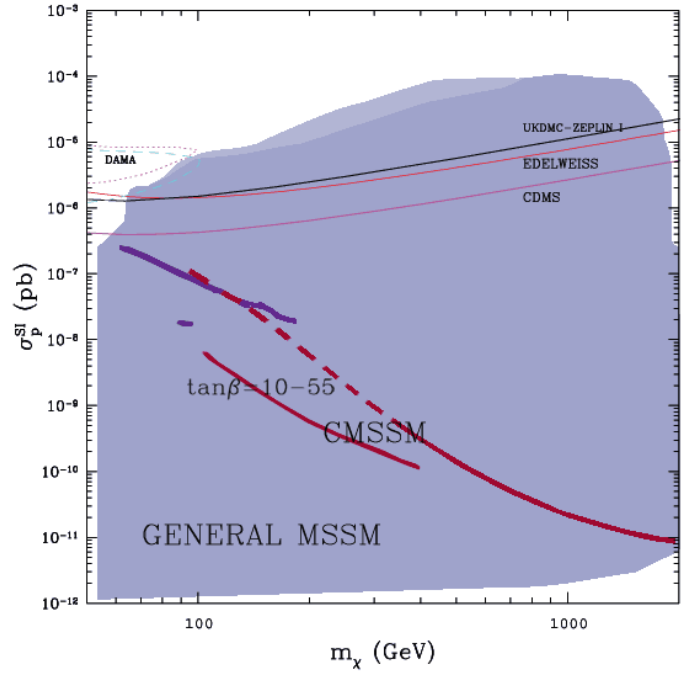

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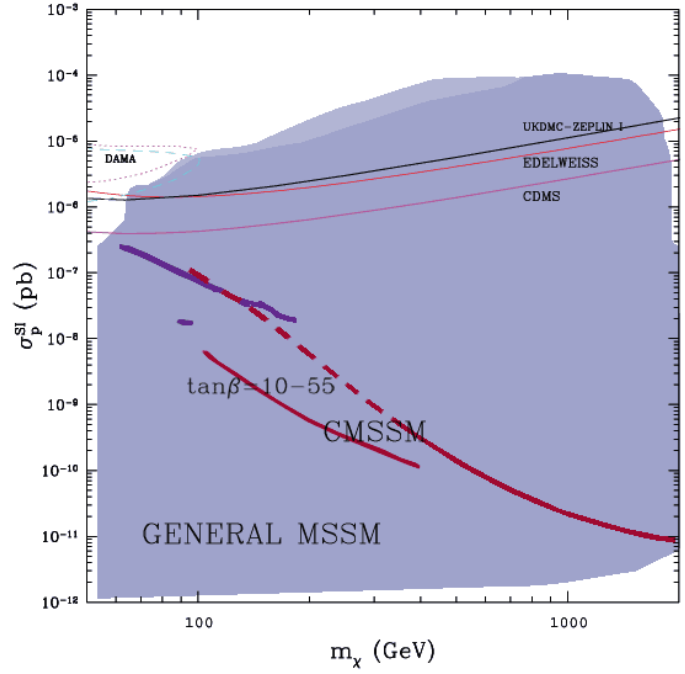

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results in over-simplified predictions

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recent development, led by 2 groups

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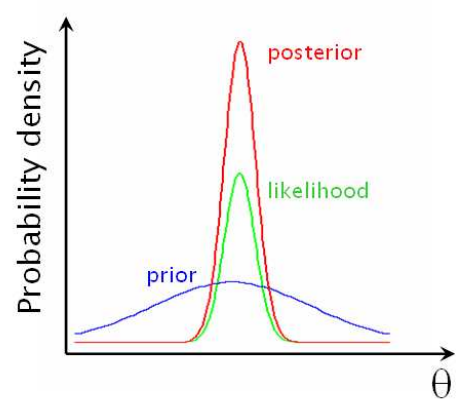

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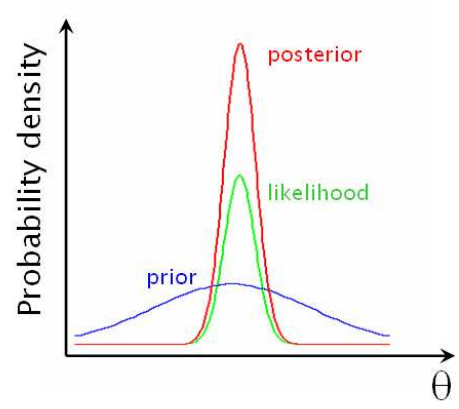
- d: data ($\Omega_{\rm CDM}h^2$, $b \to s\gamma$, m_h, etc)
- Bayes' theorem: posterior pdf

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

- $p(d|\xi) = \mathcal{L}$: likelihood
- $\pi(\theta, \psi)$: prior pdf
- $p(d)$: evidence (normalization factor)



$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{normalization factor}}$$

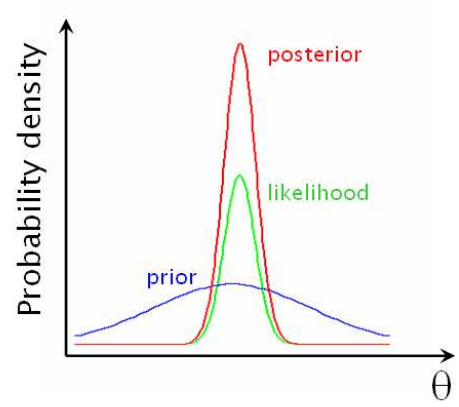
Bayesian Analysis of the CMSSM

Apply to the CMSSM: recent development, led by 2 groups

- $m = (\theta, \psi)$ – model's all relevant parameters
- CMSSM parameters $\theta = m_{1/2}, m_0, A_0, \tan\beta$
- relevant SM param's $\psi = M_t, m_b(m_b)^{\overline{MS}}, \alpha_s^{\overline{MS}}, \alpha_{\rm em}(M_Z)^{\overline{MS}}$
- $\xi = (\xi_1, \xi_2, \ldots, \xi_m)$: set of derived variables (observables): $\xi(m)$
- d: data ($\Omega_{\rm CDM}h^2$, $b \to s\gamma$, m_h, etc)
- Bayes' theorem: posterior pdf

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

- $p(d|\xi) = \mathcal{L}$: likelihood
- $\pi(\theta, \psi)$: prior pdf
- $p(d)$: evidence (normalization factor)
- usually marginalize over SM (nuisance) parameters ψ $\Rightarrow$ $p(\theta|d)$



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Impact of varying SM parameters

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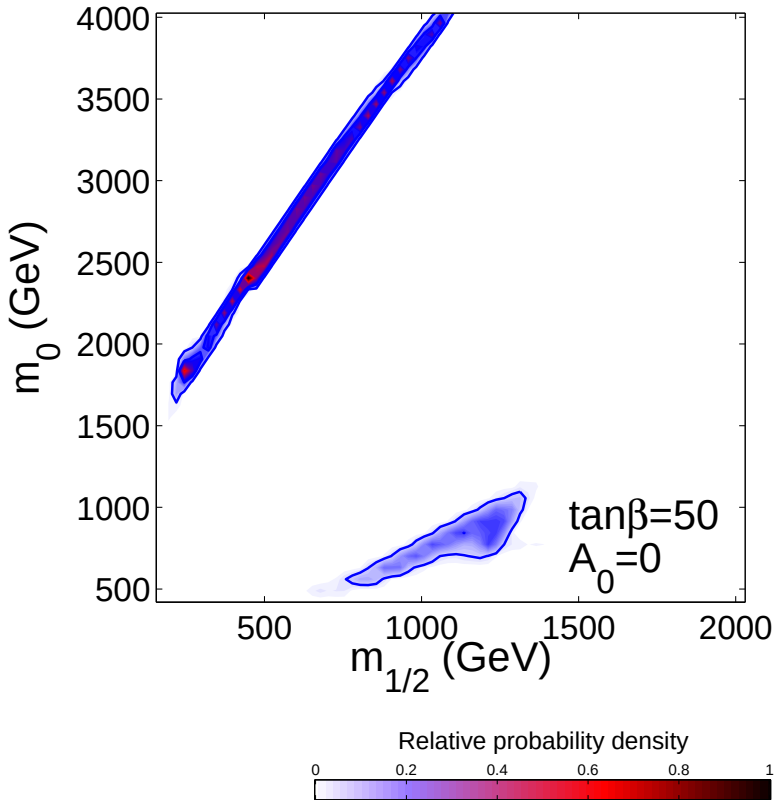
fix $\tan\beta$, A_0 + all SM param's



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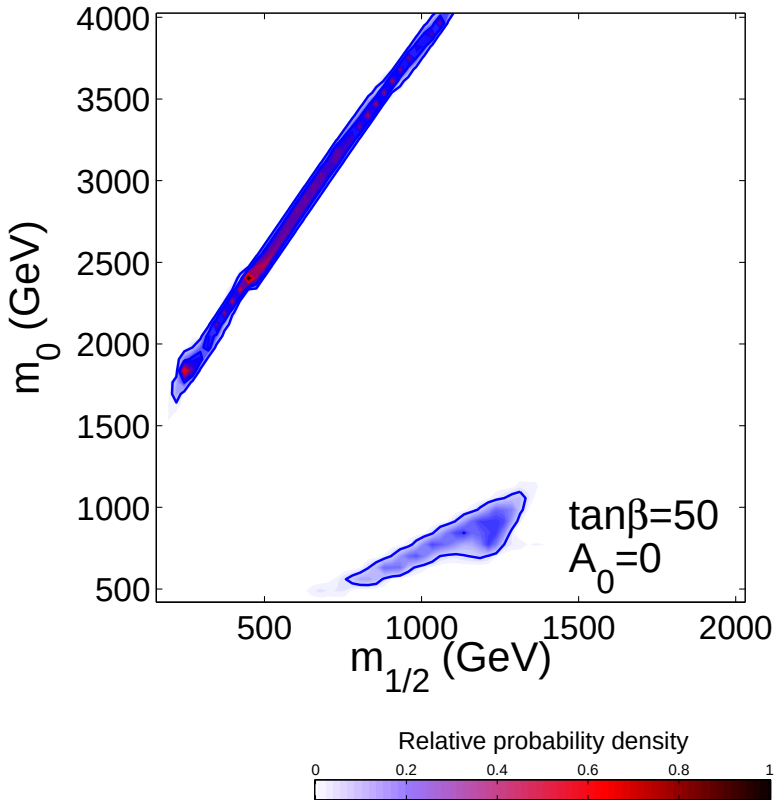
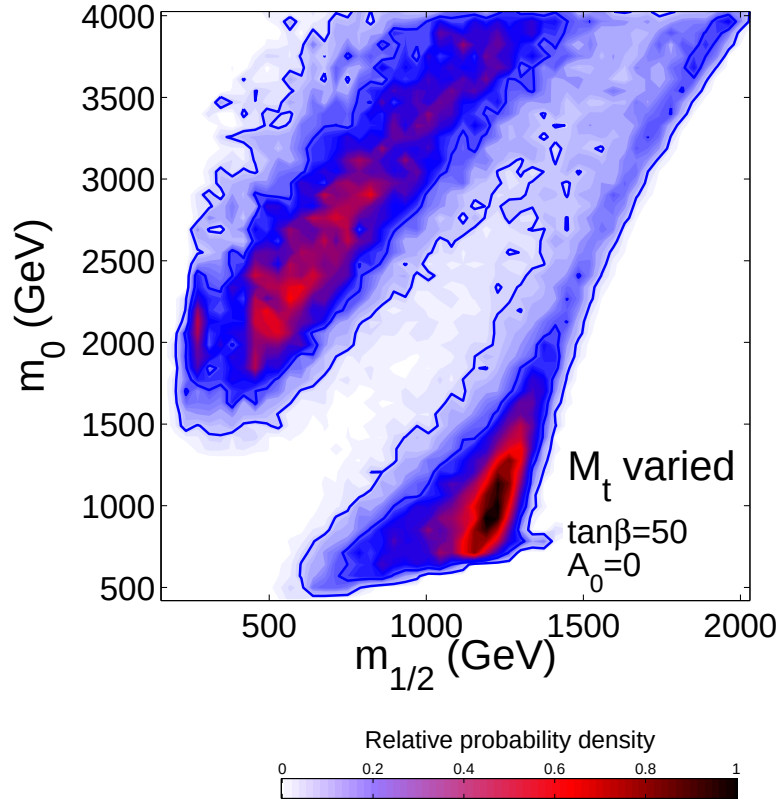


vary M_t



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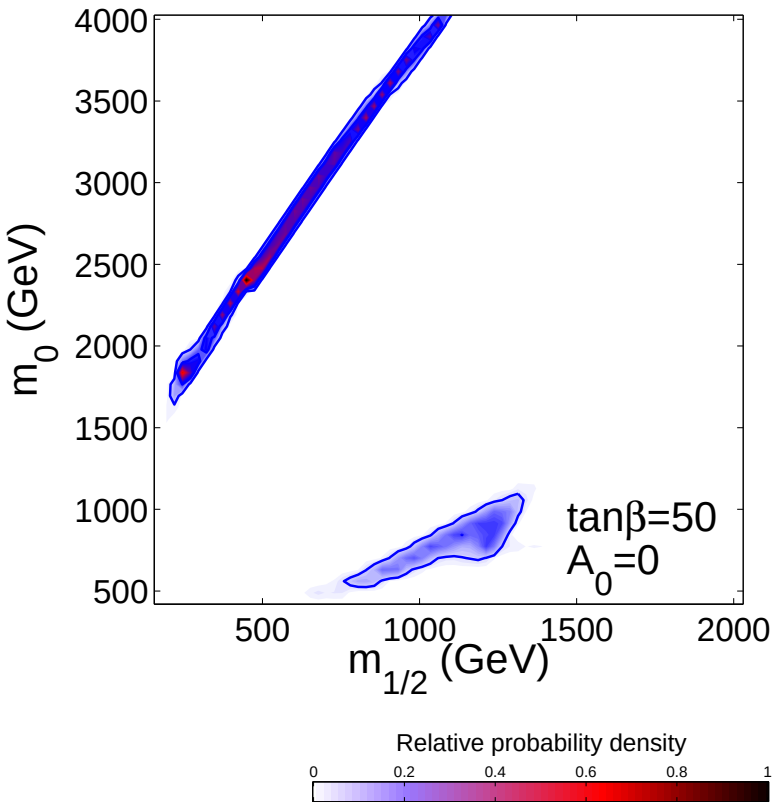

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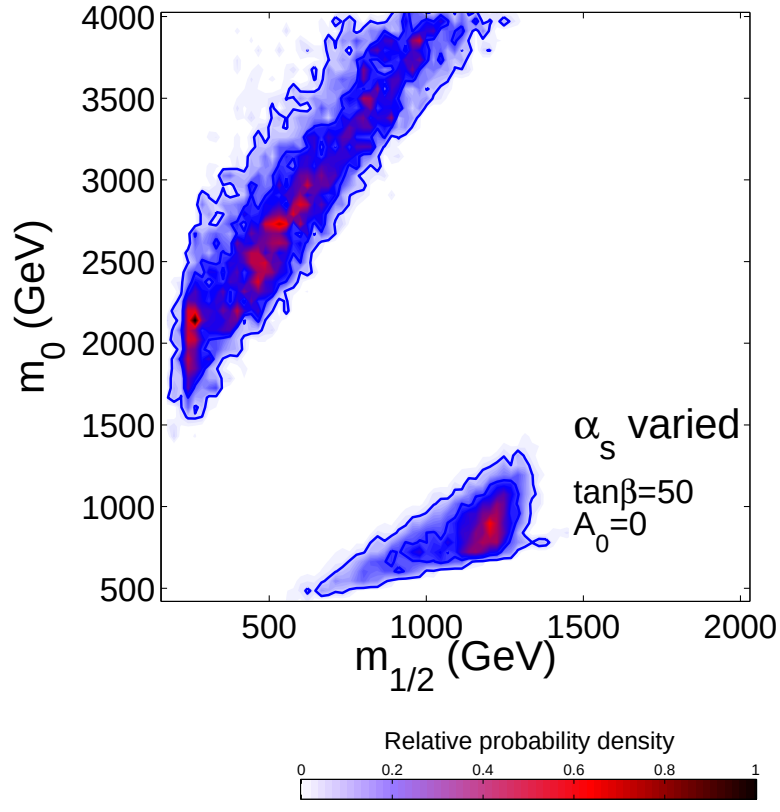

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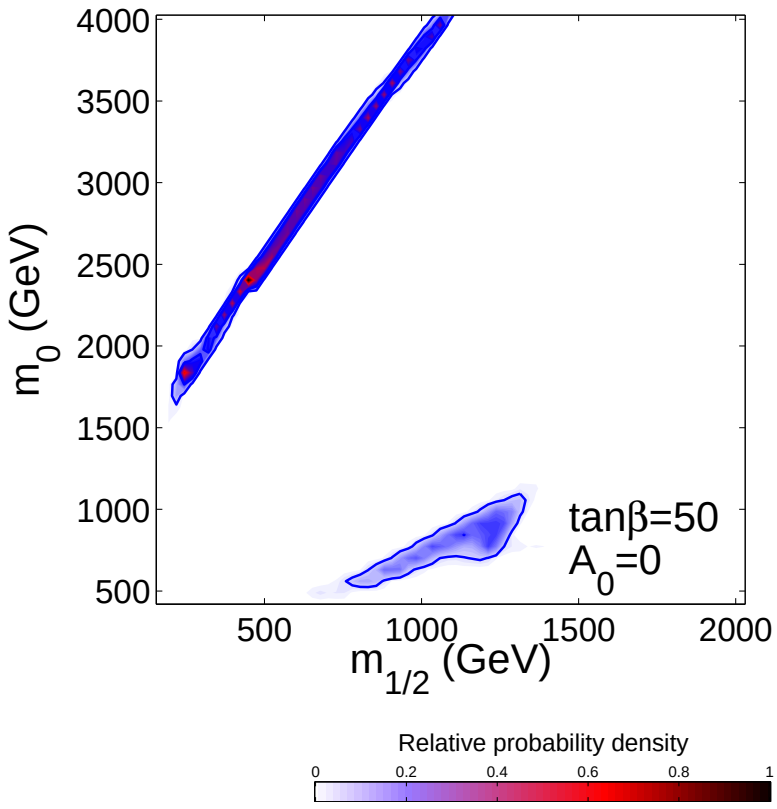

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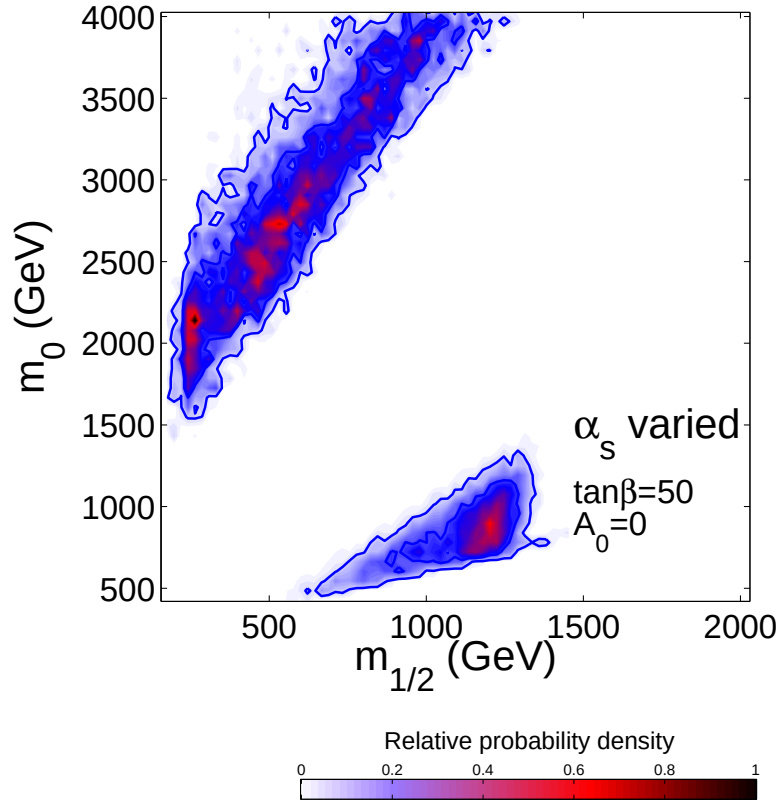

residual errors in SM parameters $\Rightarrow$ strong impact on favoured SUSY ranges

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

Bayesian Analysis of the CMSSM

Bayesian Analysis of the CMSSM

- $\theta = (m_0, m_{1/2}, A_0, \tan\beta)$: CMSSM parameters
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CMSSM parameters θ
$50\,{\rm GeV} < m_0 < 4\,{\rm TeV}$
$50\,{\rm GeV} < m_{1/2} < 4\,{\rm TeV}$
$\lvert A_0\rvert < 7\,{\rm TeV}$
$2 < \tan\beta < 62$

flat priors: SM (nuisance) parameters ψ
$160\,{\rm GeV} < M_t < 190\,{\rm GeV}$
$4\,{\rm GeV} < m_b(m_b)^{\overline{MS}} < 5\,{\rm GeV}$
$0.10 < \alpha_s^{\overline{MS}} < 0.13$
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- vary all 8 (CMSSM+SM) parameters simultaneously, apply MCMC
- include all relevant theoretical and experimental errors

Experimental Measurements

(assume Gaussian distributions)

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SM (nuisance) parameter	Mean	Error
	μ	σ (expt)
M_t	172.6 GeV	1.4 GeV
$m_b(m_b)^{\overline{MS}}$	4.20 GeV	0.07 GeV
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Derived observable	Mean	Errors	
	μ	σ (expt)	τ (th)
M_W	$\mathbf{80.398\ GeV}$	$\mathbf{25\ MeV}$	$\mathbf{15\ MeV}$
$\sin^2\theta_{\rm eff}$	$\mathbf{0.23153}$	$\mathbf{16 \times 10^{-5}}$	$\mathbf{15 \times 10^{-5}}$
$\delta a_\mu^{\rm SUSY} \times 10^{10}$	$\mathbf{29.5}$	$\mathbf{8.8}$	$\mathbf{1}$
$\mathbf{BR}(\bar{\mathrm{B}} \to \mathrm{X_s}\gamma) \times 10^4$	$\mathbf{3.55}$	$\mathbf{0.26}$	$\mathbf{0.21}$
ΔM_{B_s}	17.33	0.12	4.8
$\Omega_\chi h^2$	0.1099	0.0062	$\mathbf{0.1\ \Omega_\chi h^2}$

take w/o error: $M_Z = \mathbf{91.1876(21)\ GeV}$, $G_F = \mathbf{1.16637(1) \times 10^{-5}\ GeV^{-2}}$

Experimental Limits

Derived observable	upper/lower limit	Constraints $\xi_{\rm lim}$	τ (theor.)
$\mathbf{BR(B_s \to \mu^+\mu^-)}$	UL	$\mathbf{1.5 \times 10^{-7} \to 3 \times 10^{-8}}$	14%
m_h	LL	$\mathbf{114.4\,GeV}$ $\mathbf{(91.0\,GeV)}$	$\mathbf{3\,GeV}$
$\zeta_h^2 \equiv g^2_{ZZh}/g^2_{ZZH_{\rm SM}}$	UL	$f(m_h)$	3%
m_χ	LL	$\mathbf{50\,GeV}$	5%
$m_{\chi_1^\pm}$	LL	$\mathbf{103.5\,GeV}$ $\mathbf{(92.4\,GeV)}$	5%
$m_{\tilde{e}_R}$	LL	$\mathbf{100\,GeV}$ $\mathbf{(73\,GeV)}$	5%
$m_{\tilde{\mu}_R}$	LL	$\mathbf{95\,GeV}$ $\mathbf{(73\,GeV)}$	5%
$m_{\tilde{\tau}_1}$	LL	$\mathbf{87\,GeV}$ $\mathbf{(73\,GeV)}$	5%
$m_{\tilde{\nu}}$	LL	$\mathbf{94\,GeV}$ $\mathbf{(43\,GeV)}$	5%
$m_{\tilde{t}_1}$	LL	$\mathbf{95\,GeV}$ $\mathbf{(65\,GeV)}$	5%
$m_{\tilde{b}_1}$	LL	$\mathbf{95\,GeV}$ $\mathbf{(59\,GeV)}$	5%
$m_{\tilde{q}}$	LL	$\mathbf{318\,GeV}$	5%
$m_{\tilde{g}}$	LL	$\mathbf{233\,GeV}$	5%
$(\sigma_p^{\rm SI}$	UL	WIMP mass dependent	$\sim \mathbf{100\%})$

Note: DM direct detection $\sigma_p^{\rm SI}$ not applied due to astroph'l uncertainties (eg, local DM density)

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Take a single observable $\xi(m)$ that has been measured

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- for several uncorrelated observables (assumed Gaussian):

$$\mathcal{L} = \exp\left[-\sum_i \frac{\chi_i^2}{2}\right]$$

Probability maps of the CMSSM

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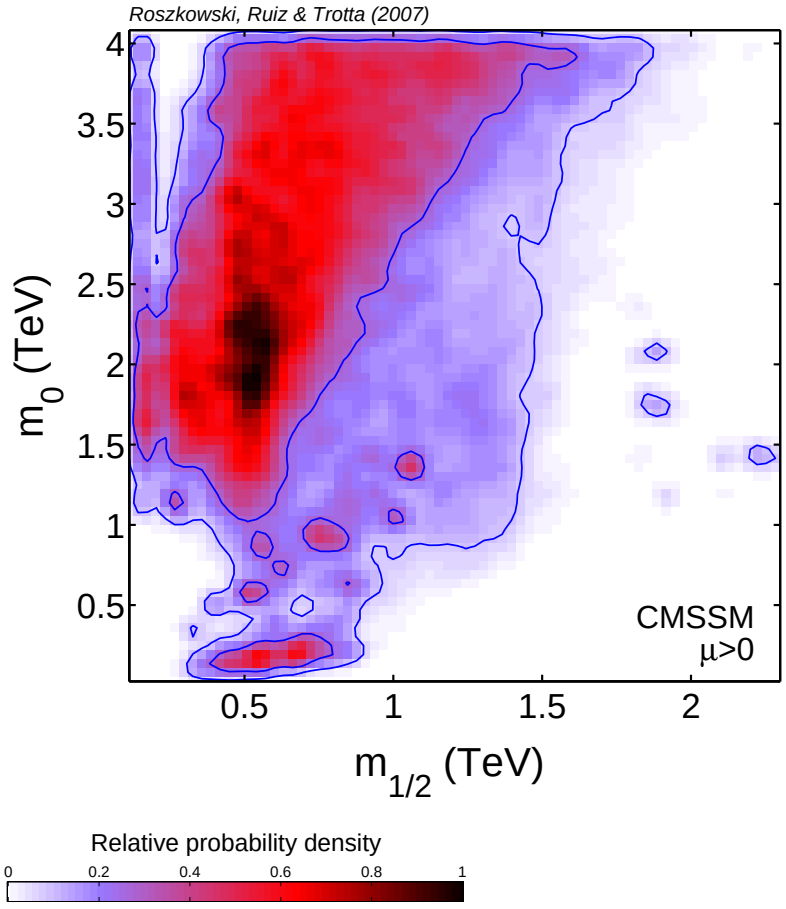
arXiv:0705.2012



- MCMC scan
- Bayesian analysis
- relative probability density fn
- flat priors
- 68% total prob. – inner contours
- 95% total prob. – outer contours
- 2-dim pdf $p(m_0, m_{1/2}|d)$
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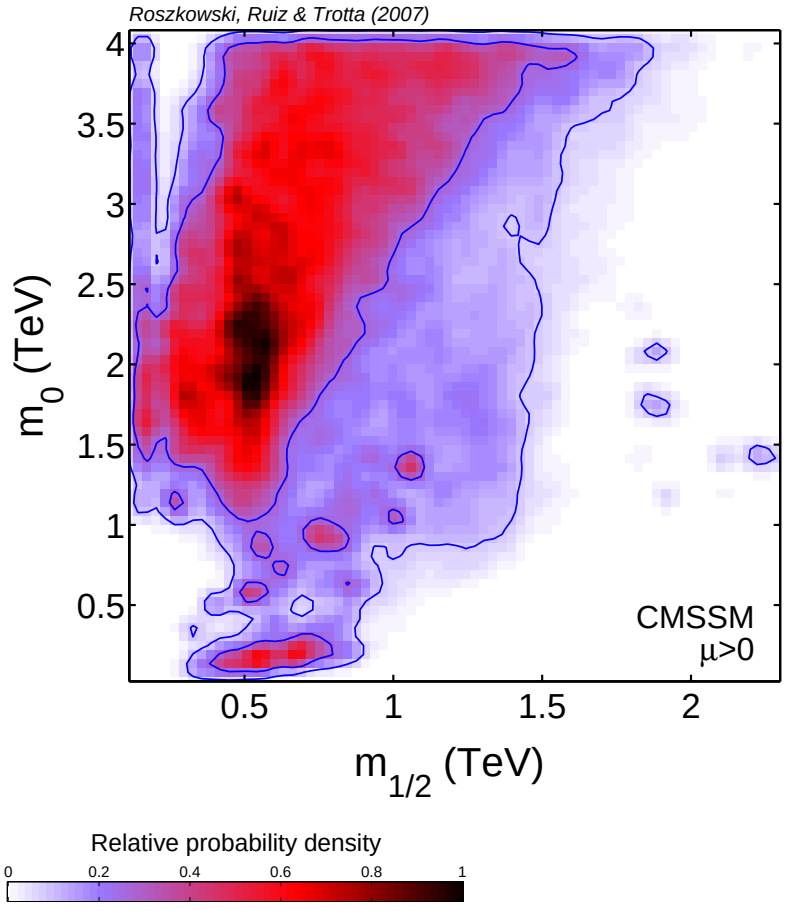

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similar study by Allanach+Lester(+Weber)

see also, Ellis et al (EHOW, χ^2 approach, no MCMC, they fix SM parameters!)

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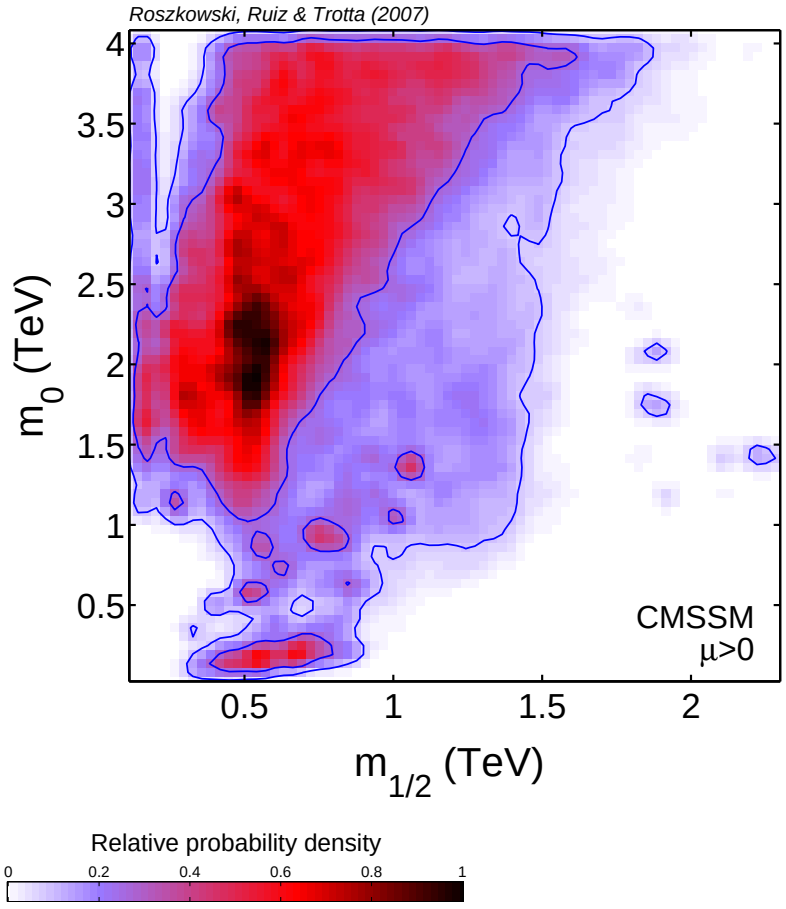

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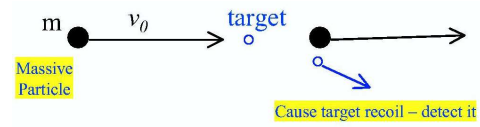
unlike others (except for A+L), we vary also SM parameters

SUSY: Prospects for direct detection

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



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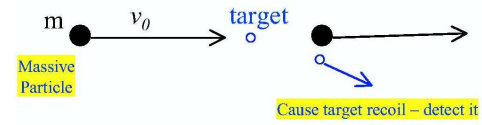
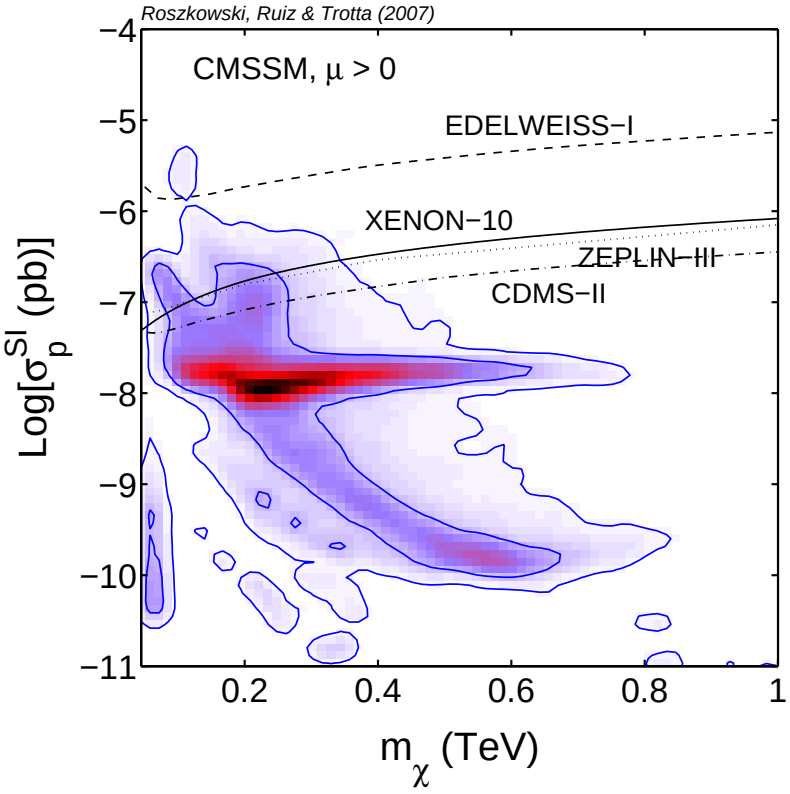


CMSSM: global scan, MCMC



internal (external): $\mathbf{68\%}$ ($\mathbf{95\%}$) region

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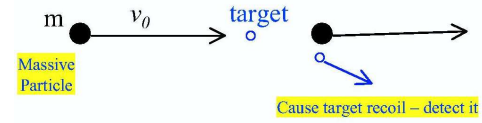
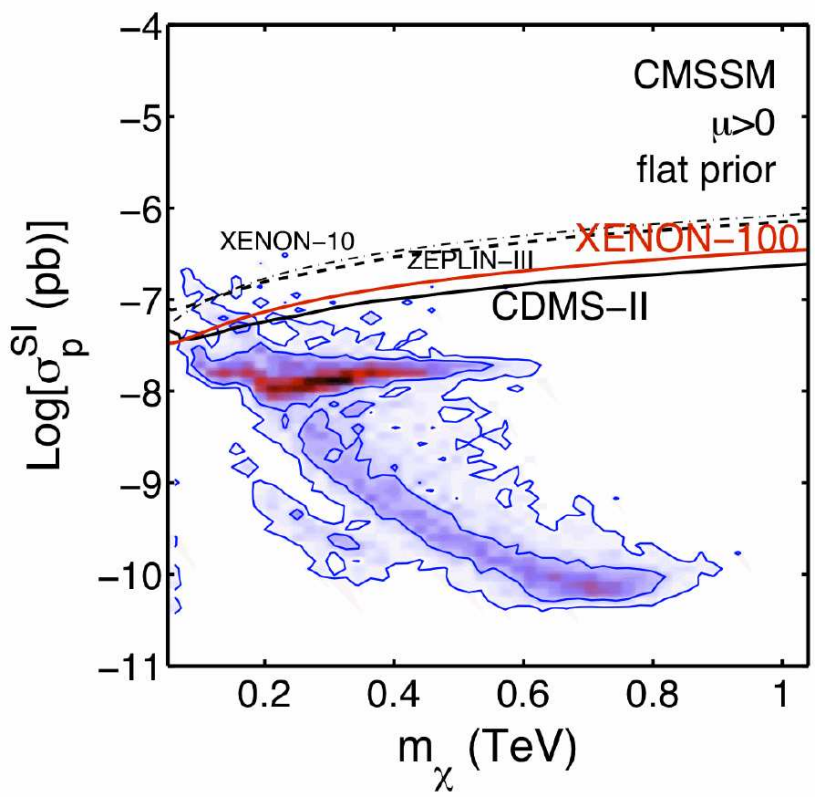


CMSSM: global scan, Nested Sampling



XENON-100 and CDMS-II:

$\sigma_p^{\mathrm{SI}} \lesssim 10^{-7}$ 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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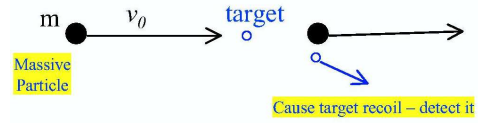

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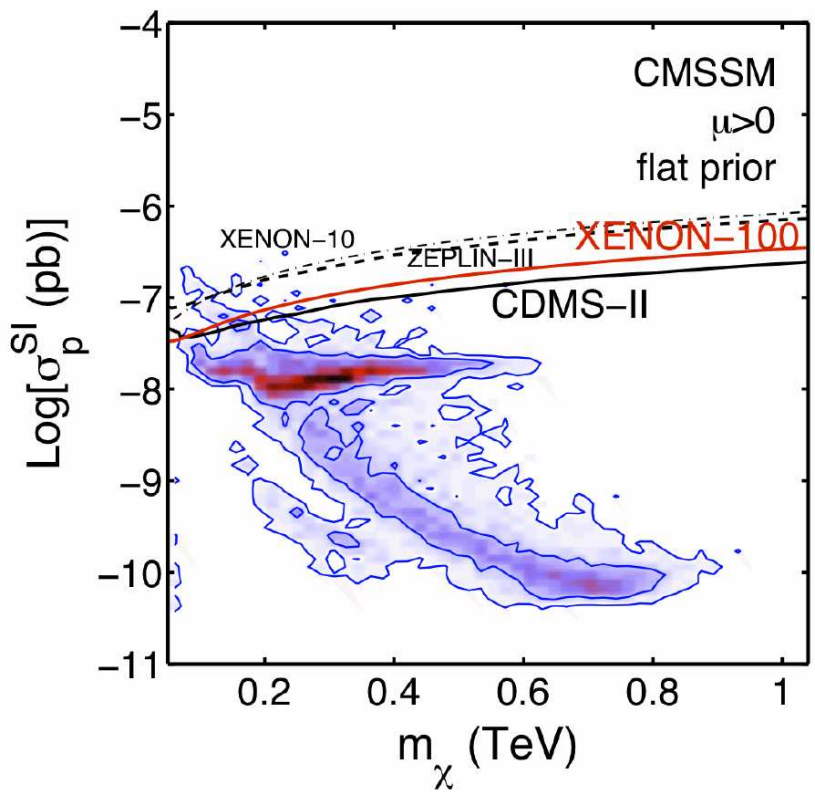

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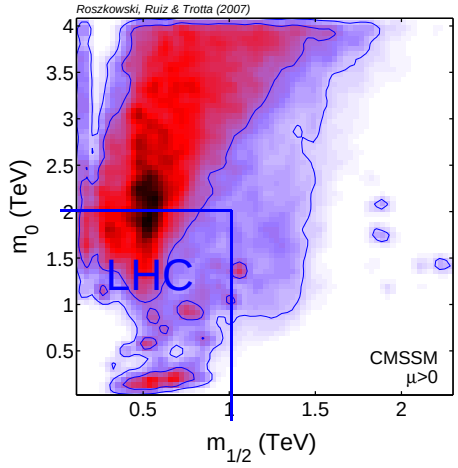

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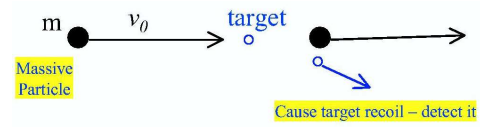

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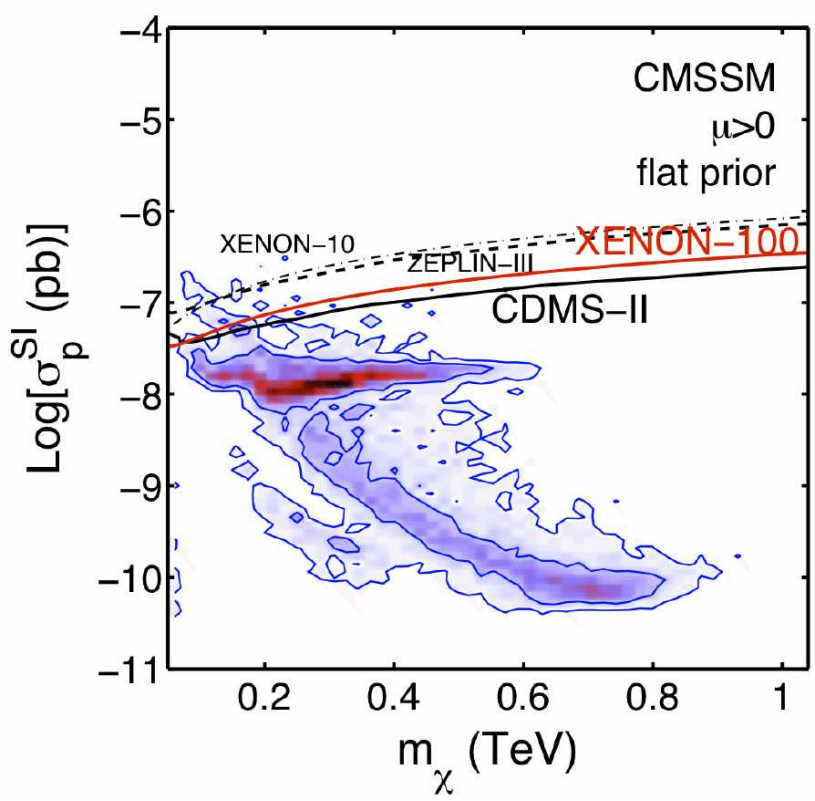

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internal (external): 68% (95%) region

$\Rightarrow$ 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

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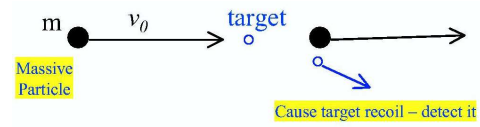

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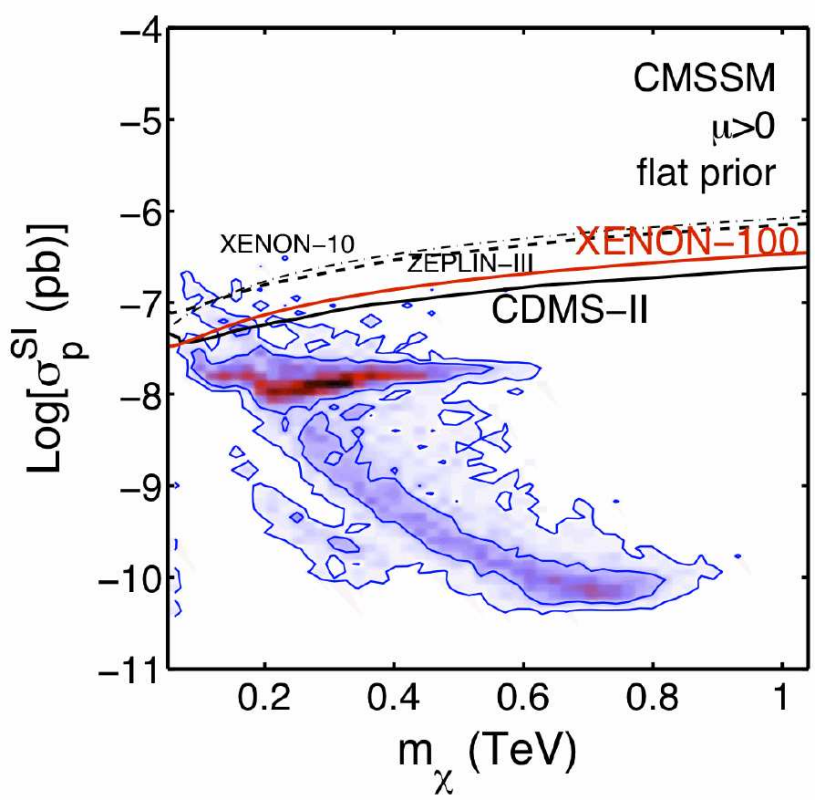

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$\Rightarrow$ DD: prospects look very good

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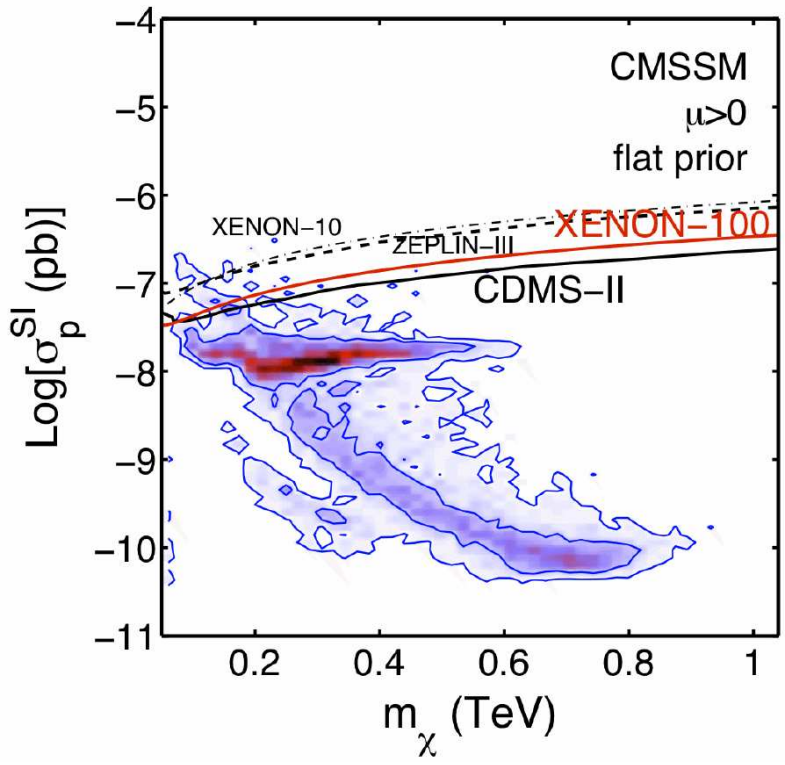

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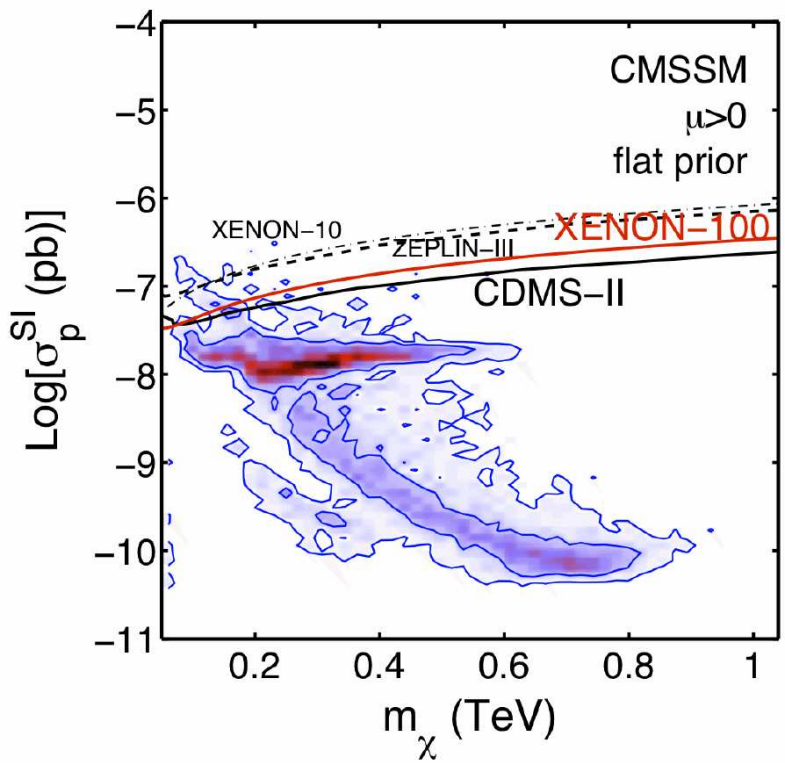
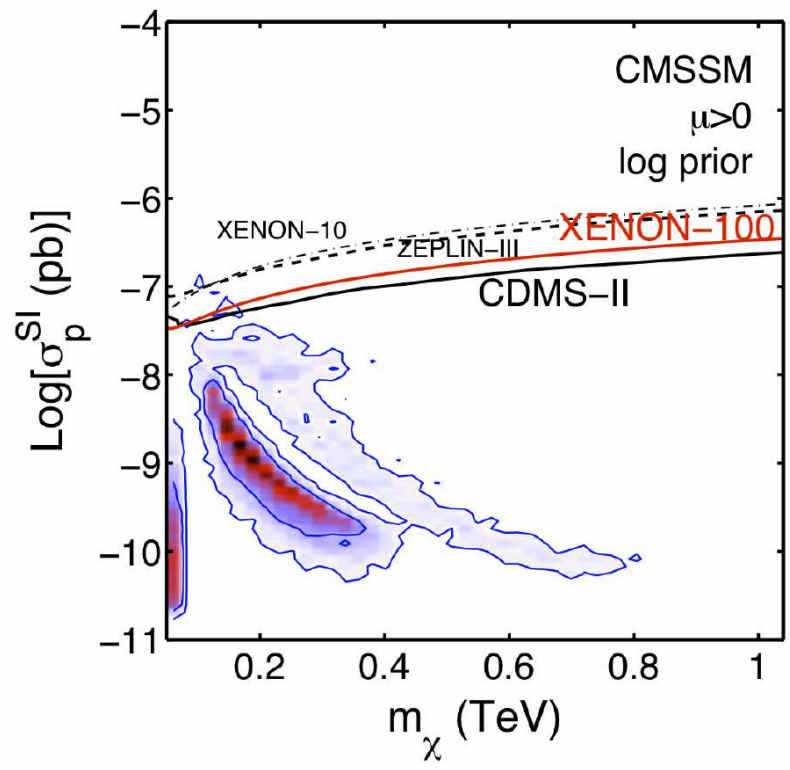


flat in $\log(m_0)$, $\log(m_{1/2})$



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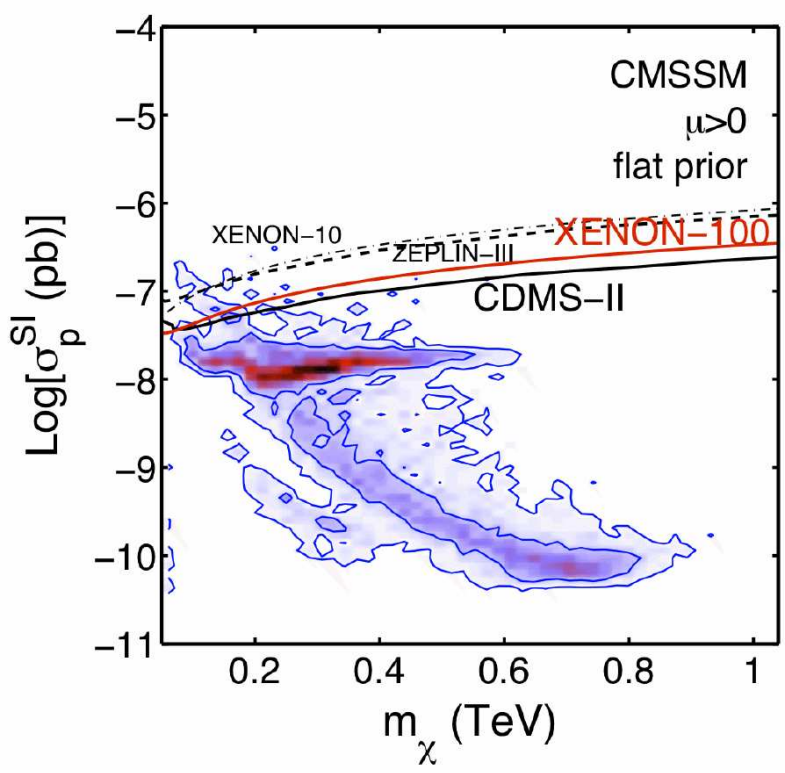

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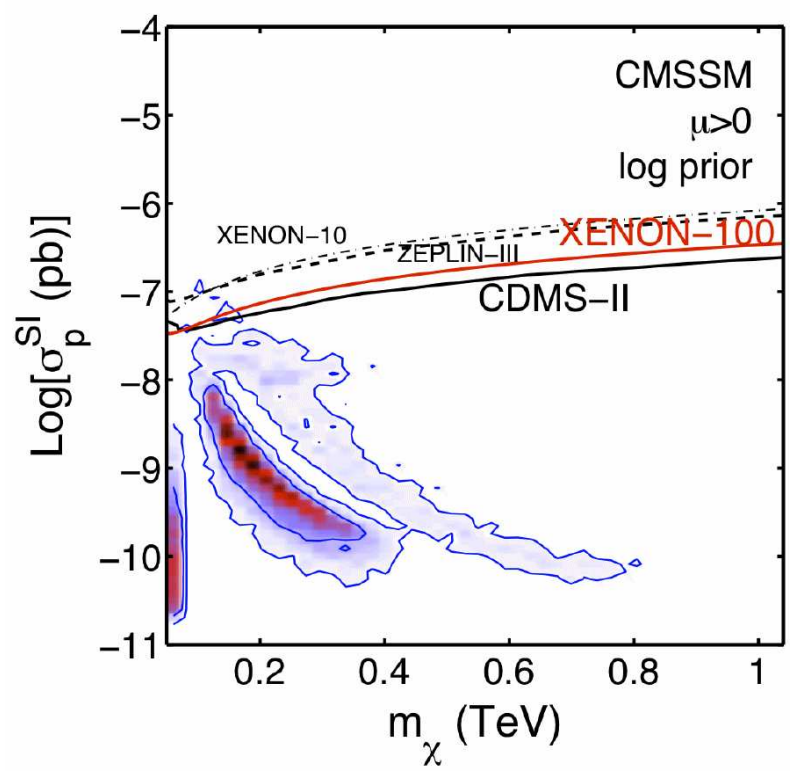


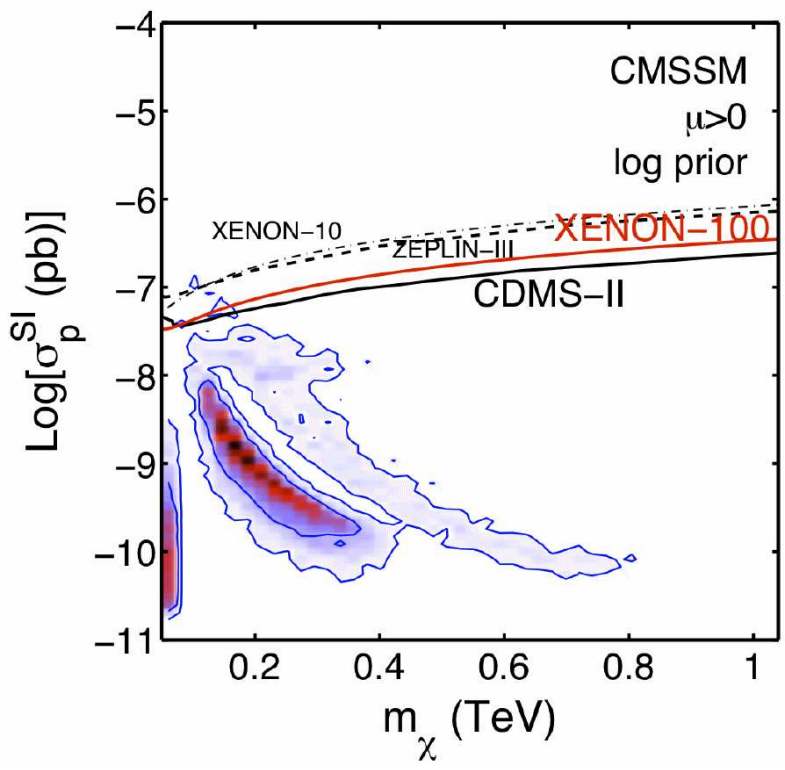
- still strong prior dependence (data not yet constraining enough)
- both priors: most regions above some 10^{-10} pb $\Rightarrow$ good news for DM expt
- LHC reach: $m_\chi \lesssim 400 - 500\,\mathrm{GeV}$ $\Rightarrow$ additional vital info

Bayesian vs frequentist

CMSSM:

Bayesian vs frequentist

CMSSM:



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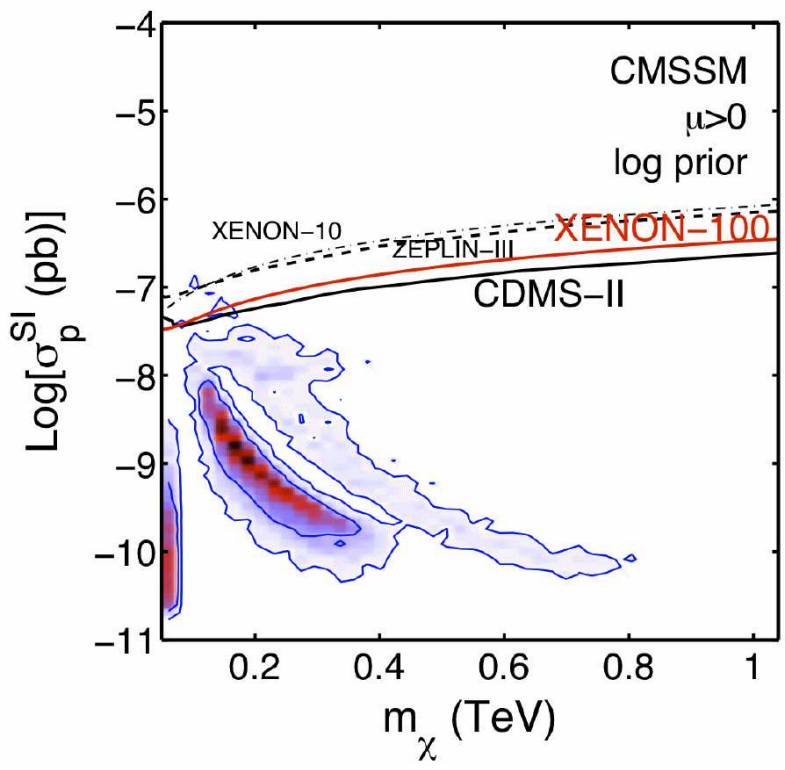
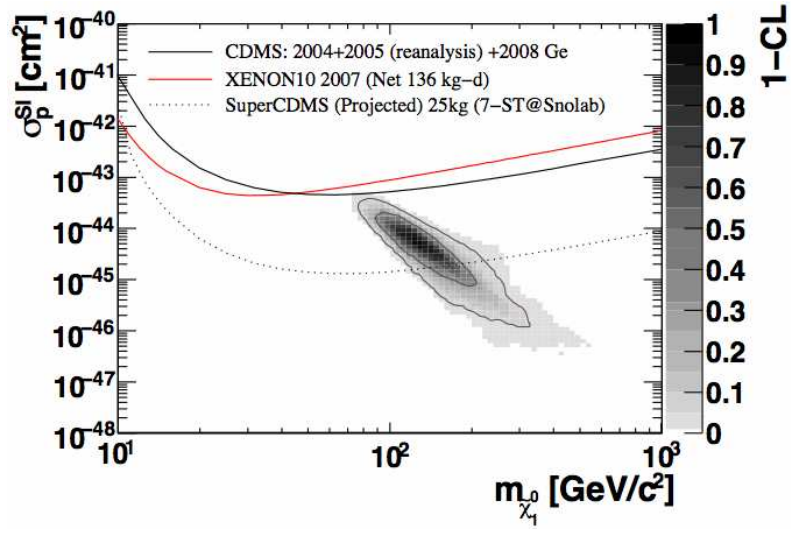


Buchmueller, et al (09)



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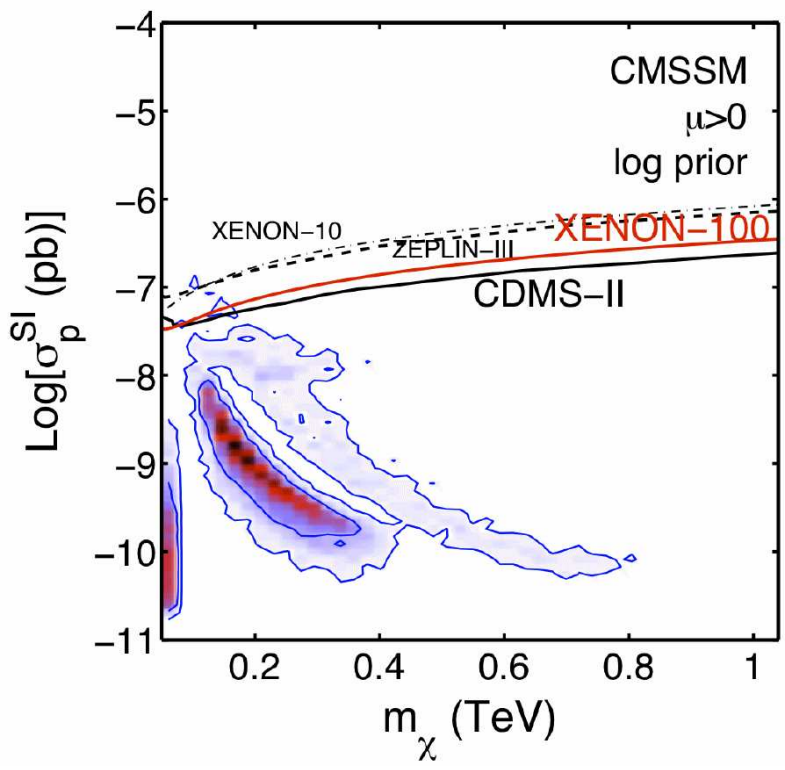

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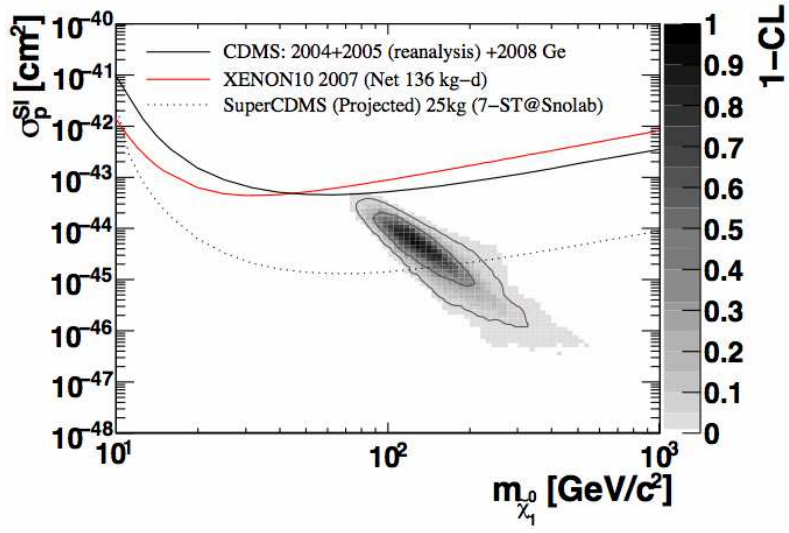

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- reasonable agreement

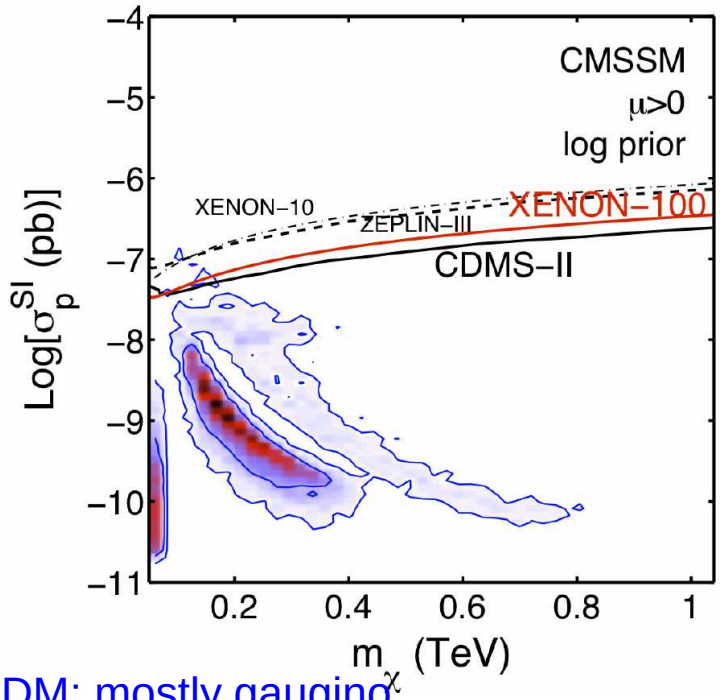
SUSY models and DM direct detection

Bayesian analysis, log priors

SUSY models and DM direct detection

Bayesian analysis, log priors

Constrained MSSM



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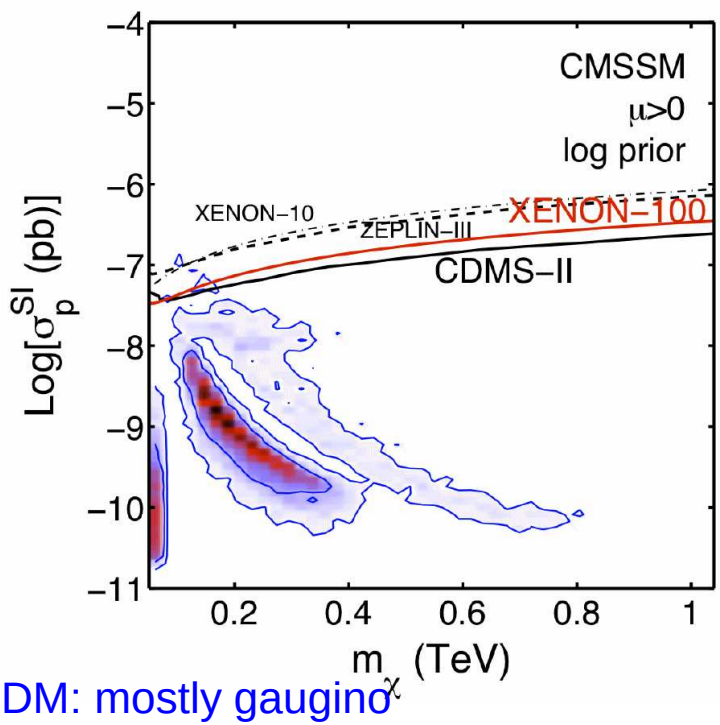

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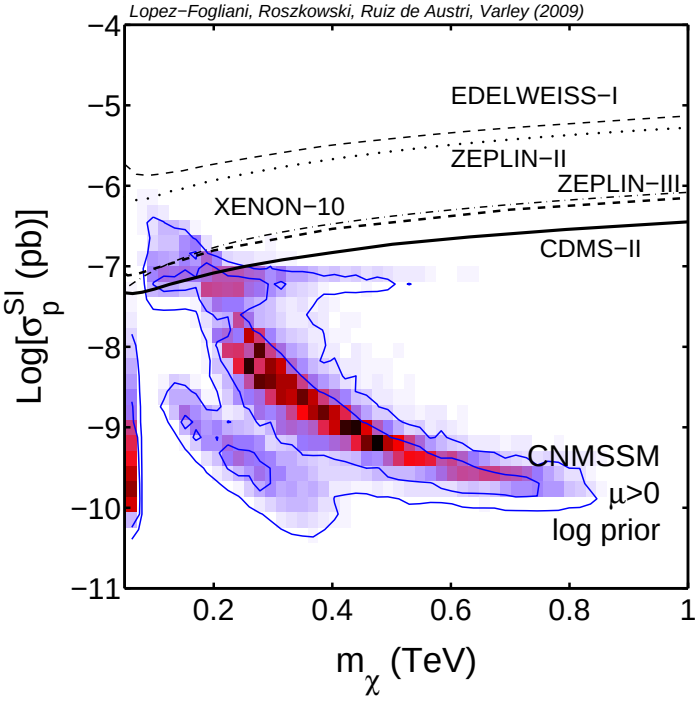
add singlet Higgs S; λS^3



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⇒ fairly similar pattern

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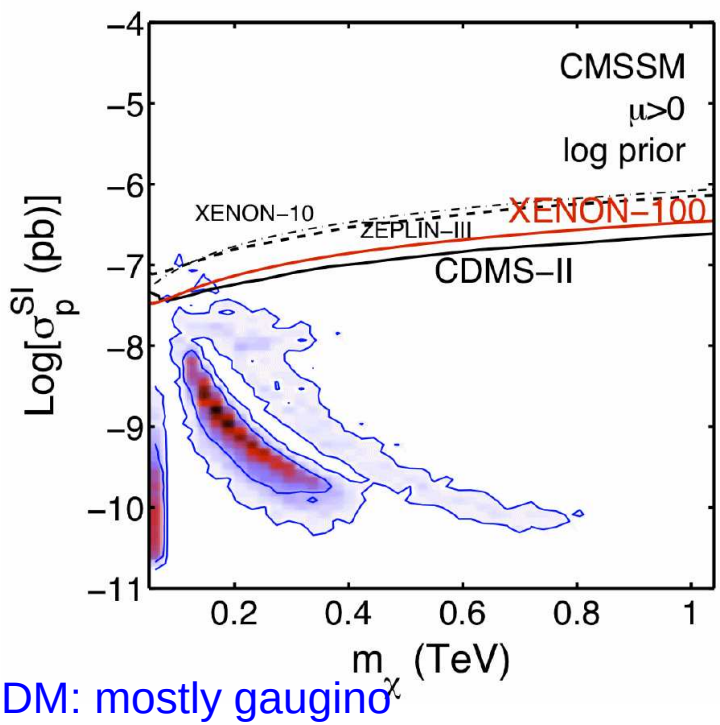

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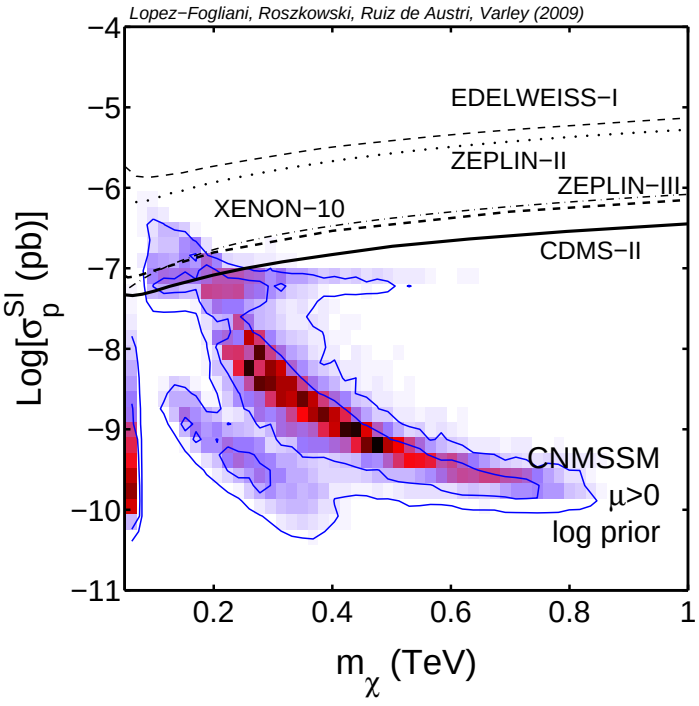

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many collider signatures also (likely to be) similar

⇒ LHC, DM expt: it may be hard to discriminate among models

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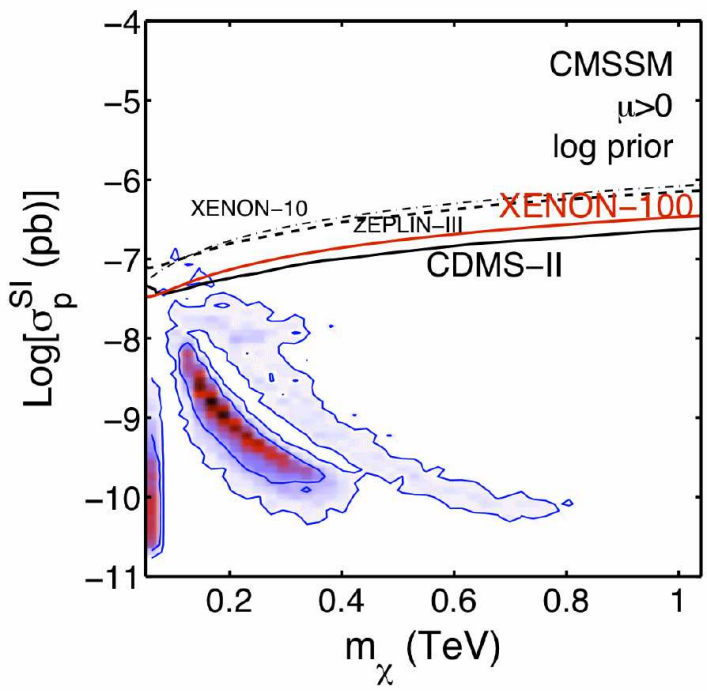

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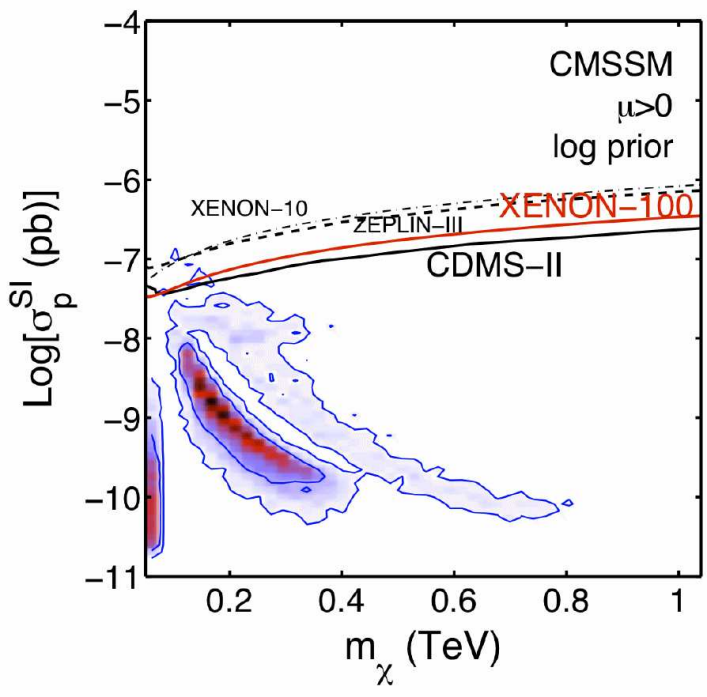

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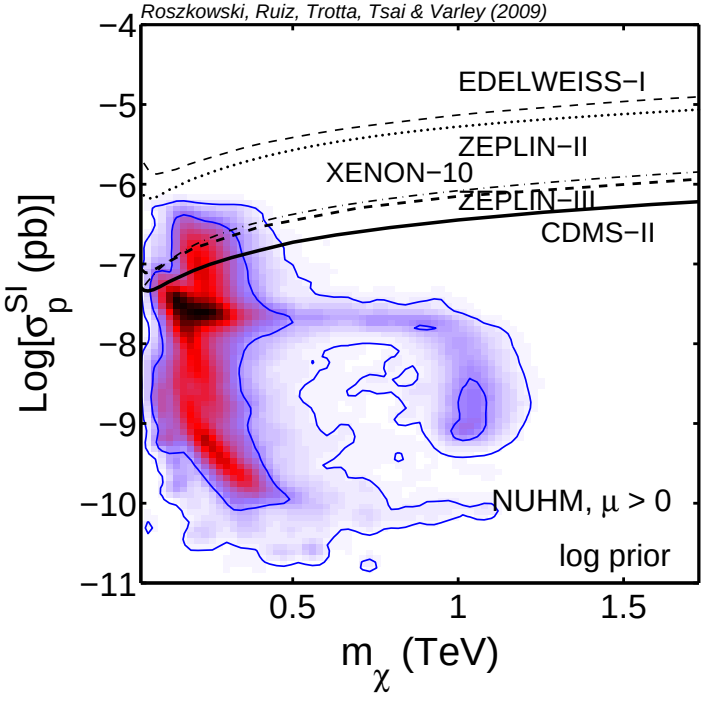

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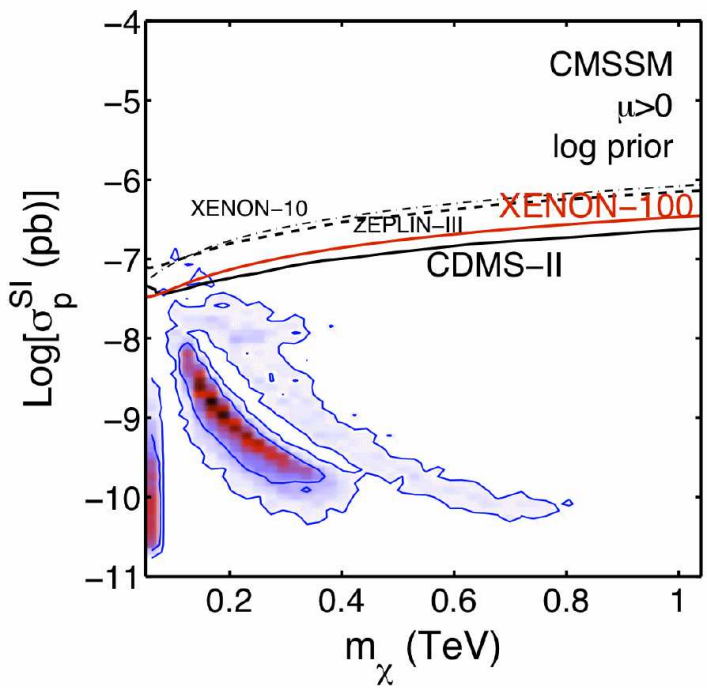

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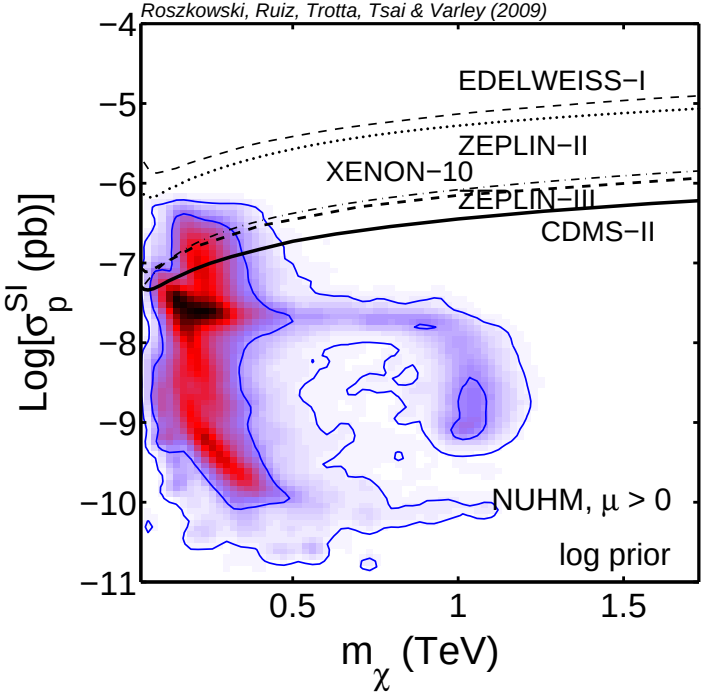

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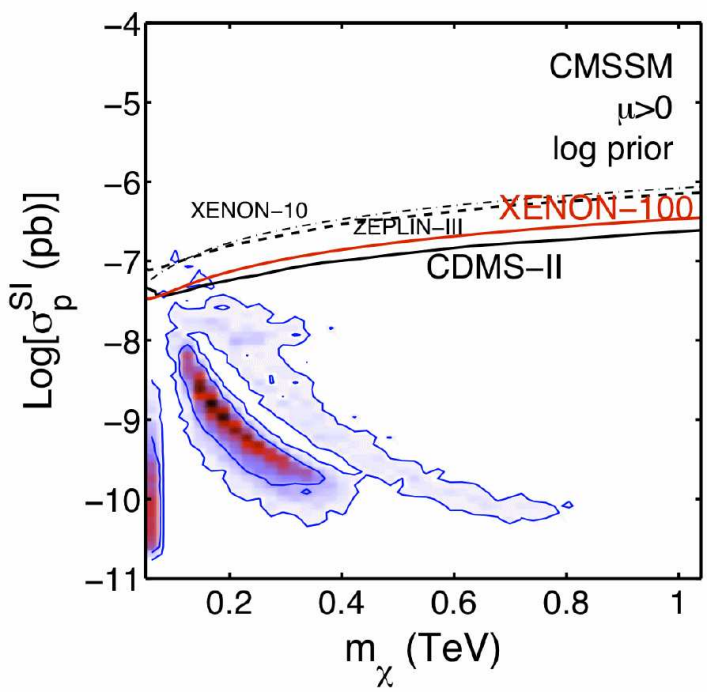

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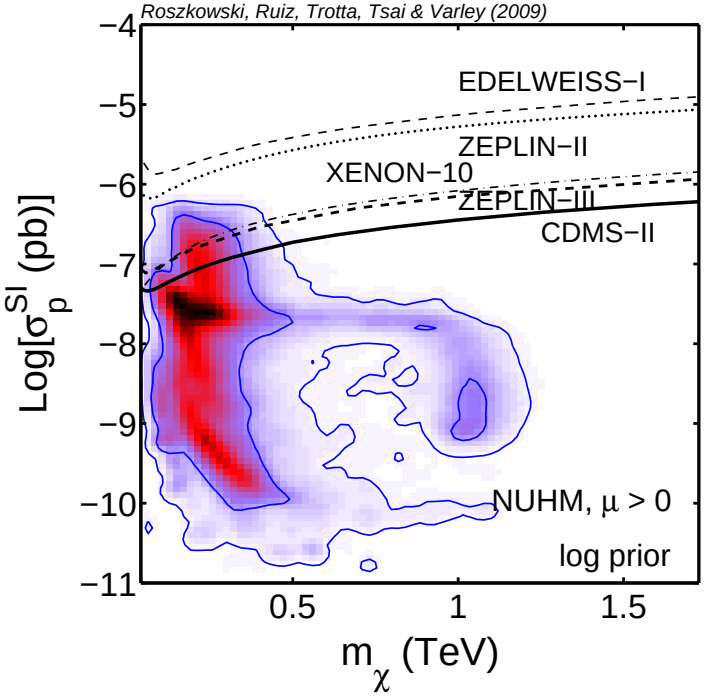

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Indirect detection

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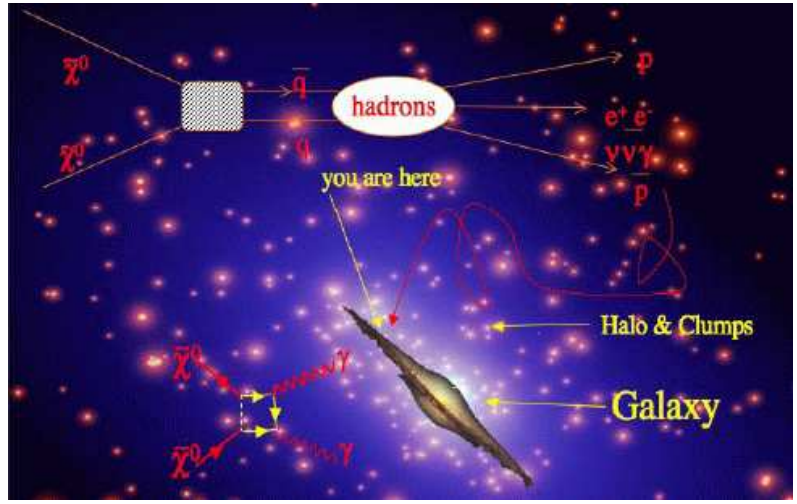

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Much activity in connection with:

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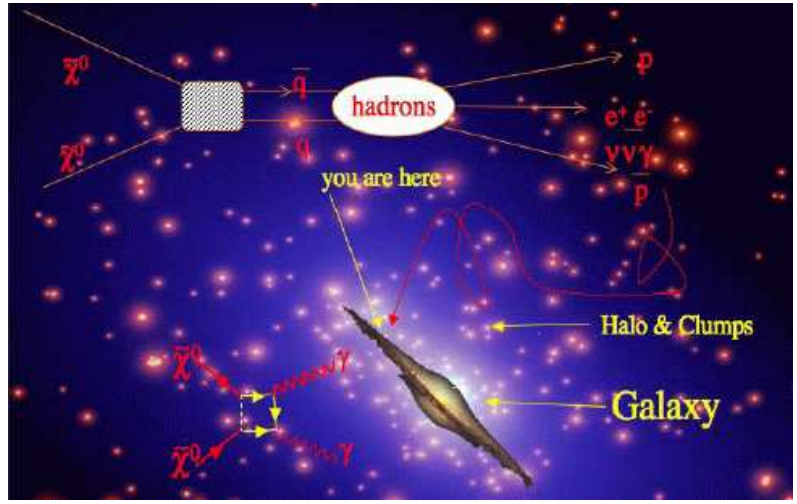

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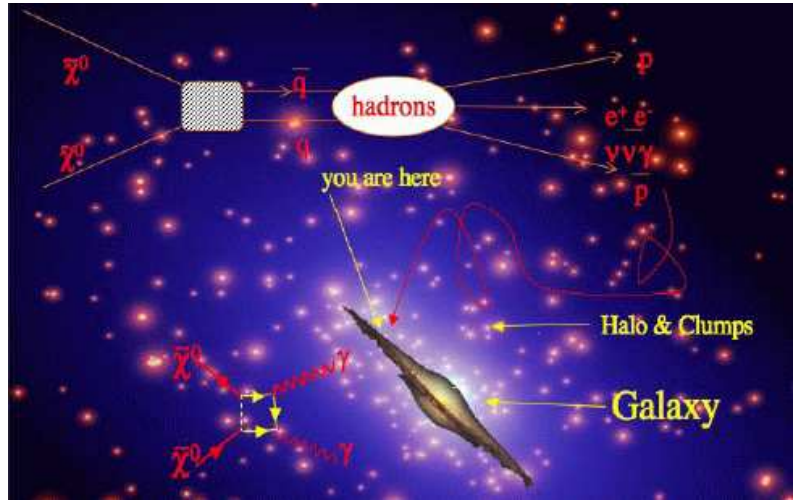

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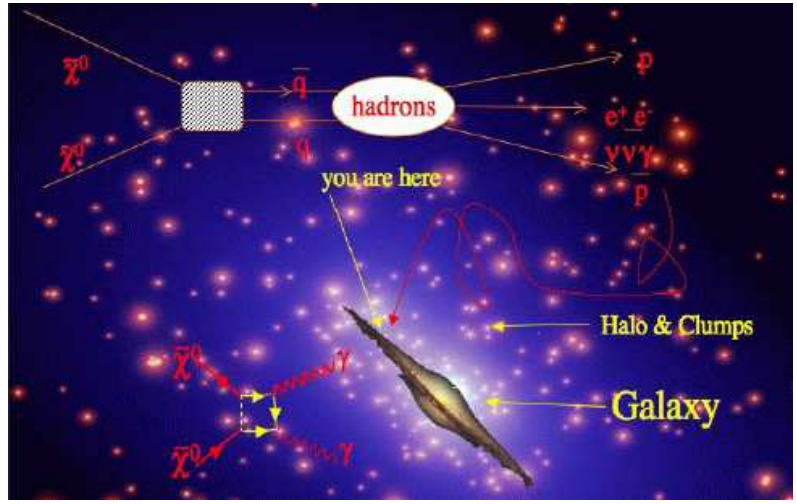

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- H.E.S.S, ATCs, ...

SUSY and positron flux

Bayesian posterior probability maps

BF=1

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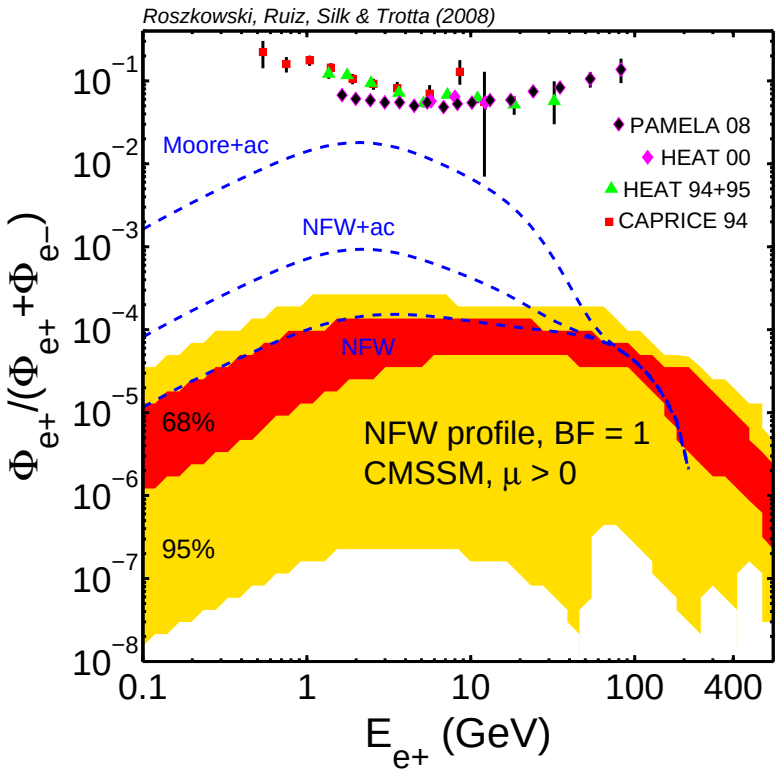
CMSSM, flat priors, NFW



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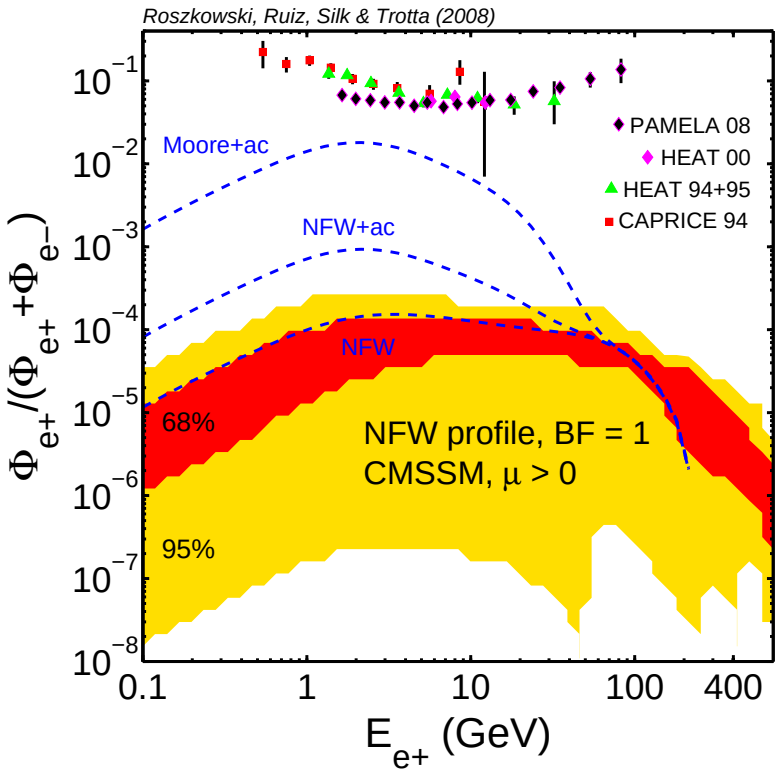

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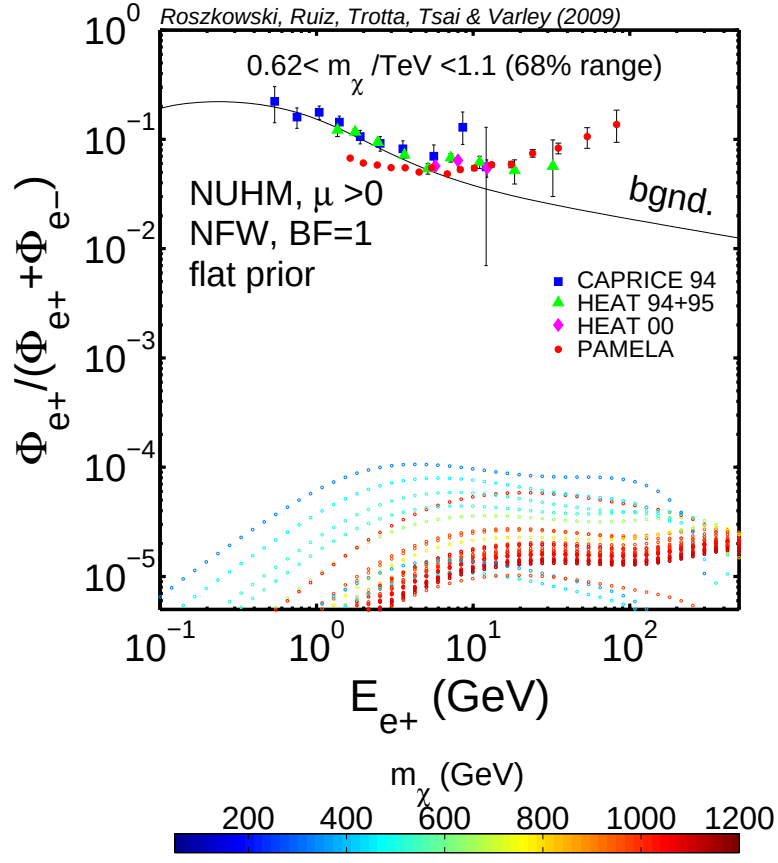

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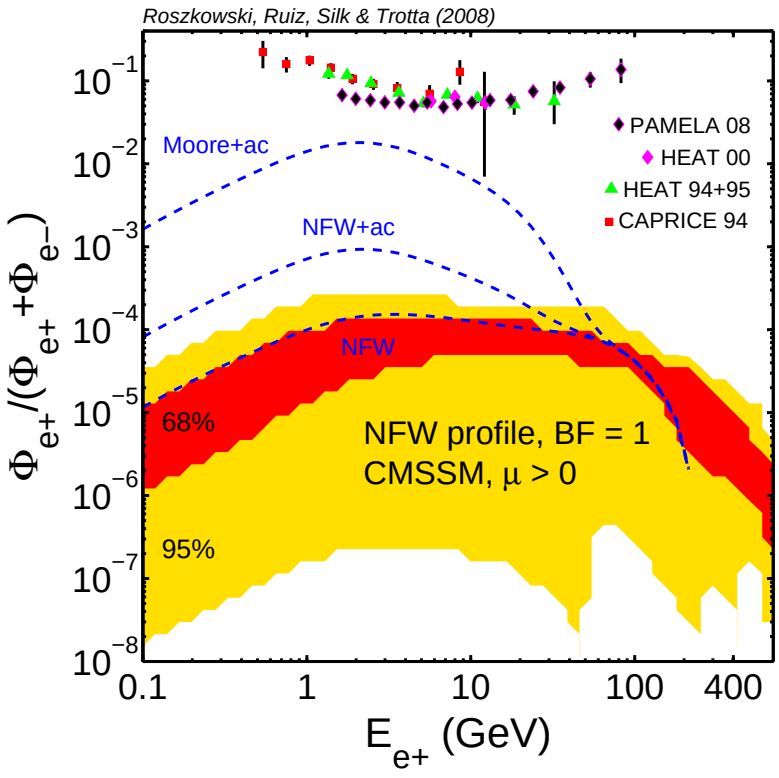

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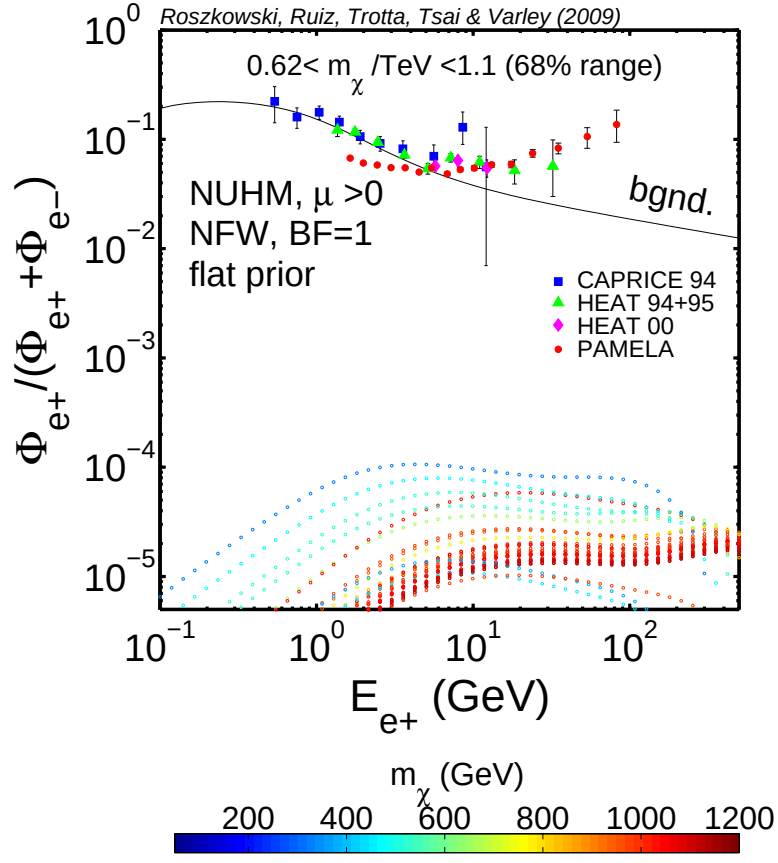

simple unified SUSY models (CMSSM, NUHM): inconsistent with PAMELA's e^+ claim

...even for unrealistically large boost factors

(flux scales linearly with boost factor)

Gamma Rays From DM Annihilation

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- diffuse γ radiation from direction ψ from the GC:

l.o.s - line of sight

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi) = \sum_i \frac{\sigma_i v}{8\pi m_\chi^2} \frac{dN_\gamma^i}{dE_\gamma} \int_{\mathrm{l.o.s.}} dl \rho_\chi^2(r(l, \psi))$$

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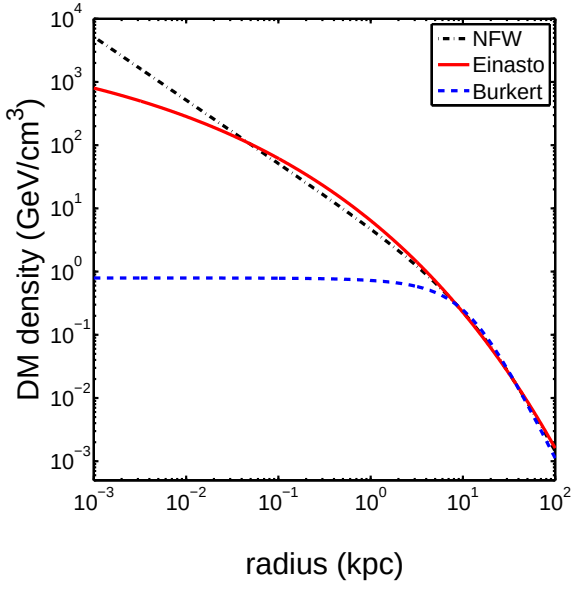

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some representative halo profiles

Diffuse GRs from the GC

use Fermi/GLAST parameters

Bayesian posterior probability maps

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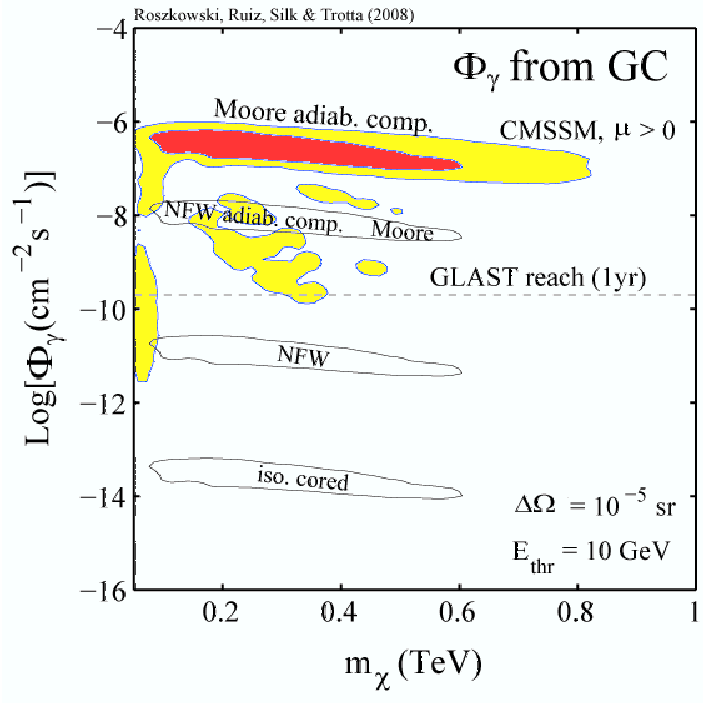

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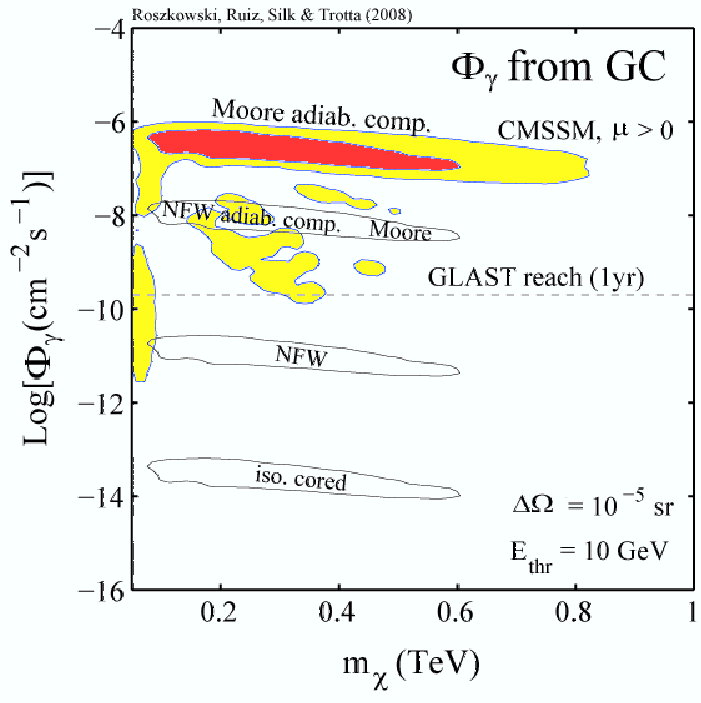

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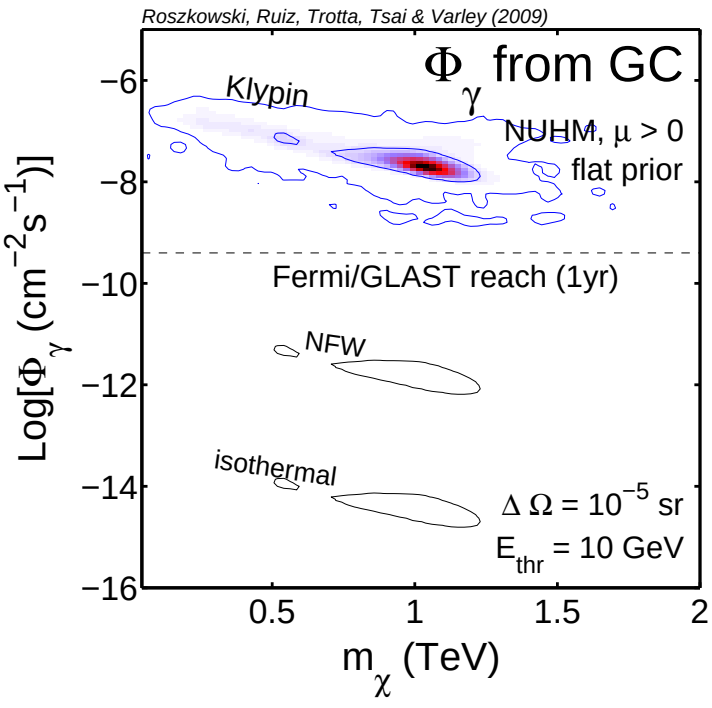

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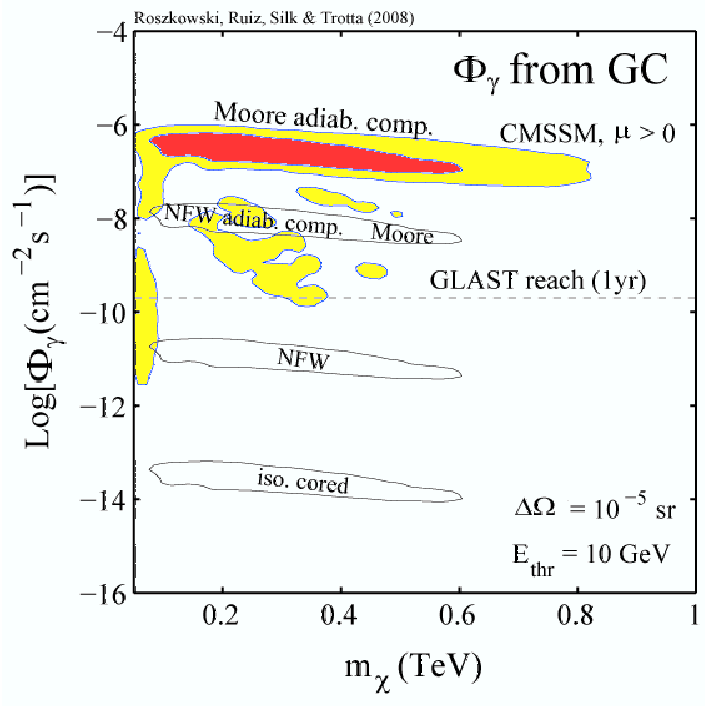

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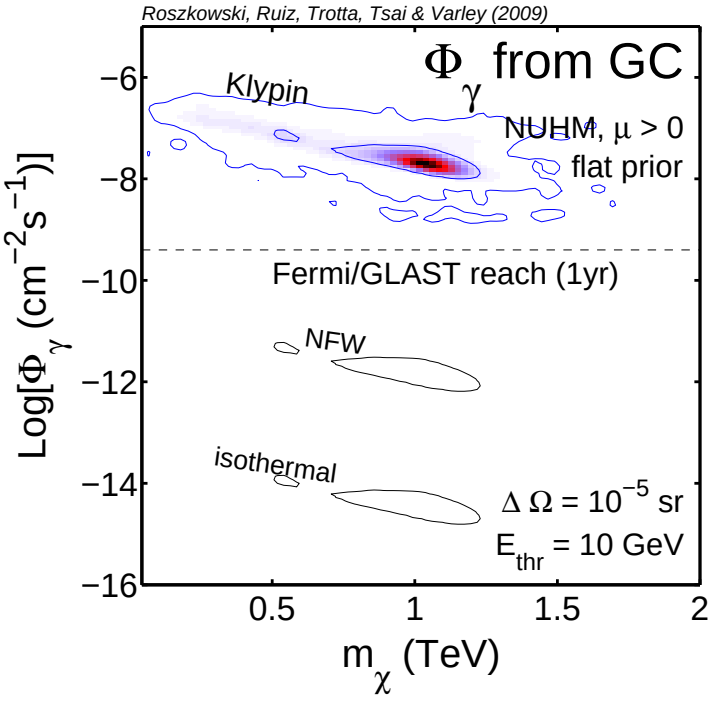

⇒ WIMP signal at Fermi/GLAST: outcome depends on halo cuspiness at GC

a conclusion of several different studies

Tests of DM in the Galactic Center

ratio of fluxes is independent of particle physics input

$$R^{\rm GC}_{d\Phi_\gamma/dE_\gamma} = \frac{\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi)}{\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\psi=0)} = \frac{\langle J(\psi)\rangle_{\Delta\Omega}}{\langle J(\psi=0)\rangle_{\Delta\Omega}} = \frac{\int_{\rm l.o.s.} dl'\,\rho^2_\chi(r(l',\psi))}{\int_{\rm l.o.s.} dl'\,\rho^2_\chi(r(l',\psi=0))}$$

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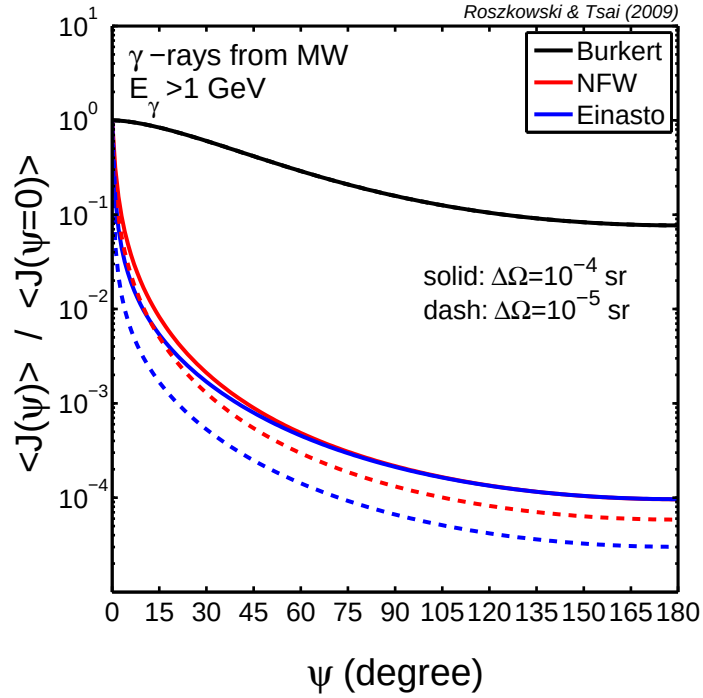
arXiv:0909.1529



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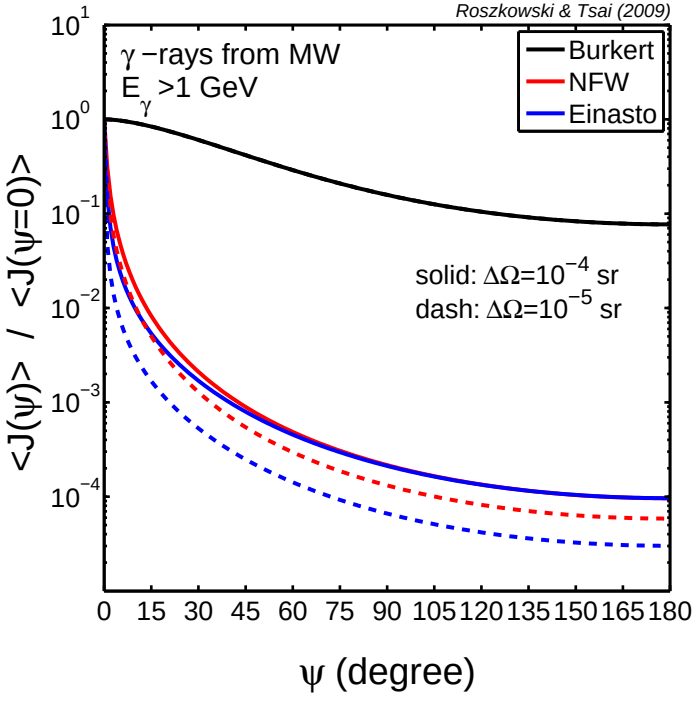

Signal of DM if:

- data follows one of the curves
- measured ratio *remains the same* in the Galactic plane *and* the plane normal to the Galactic plane
- astro sources (bgnd): bigger contribution from the MW disk

  DM can possibly dominate within $\mathbf{2-3^\circ}$ of the GC
- data $\Rightarrow$ can get handle on DM halo density slope in the GC

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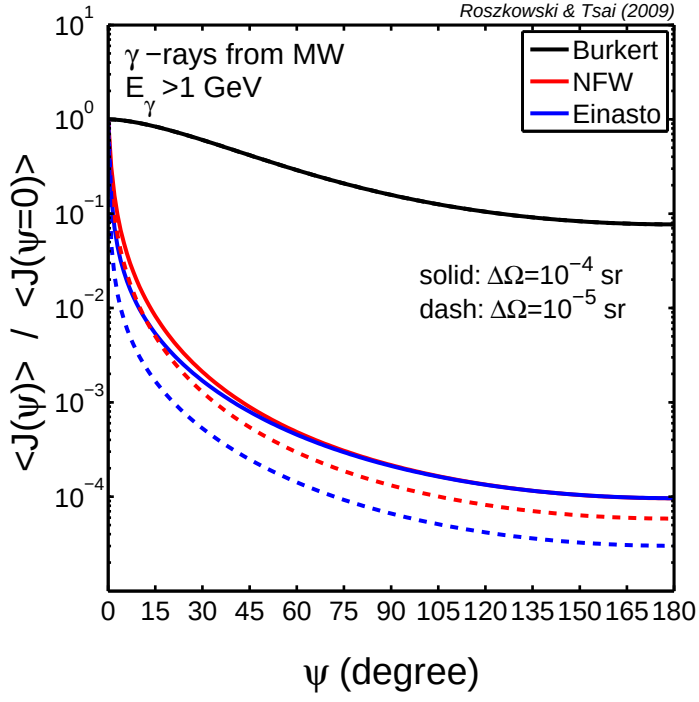

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$\Rightarrow$ would provide an unambiguous signal of DM origin

reason: only DM distribution around GC is (likely to be) spherical and $\propto \rho_\chi^2$

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enhance signal by integrating over energy and solid angle

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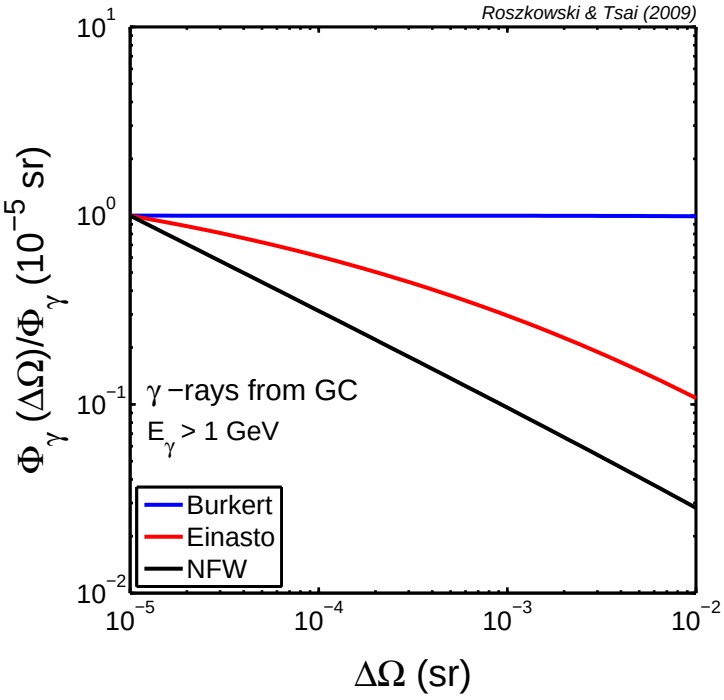

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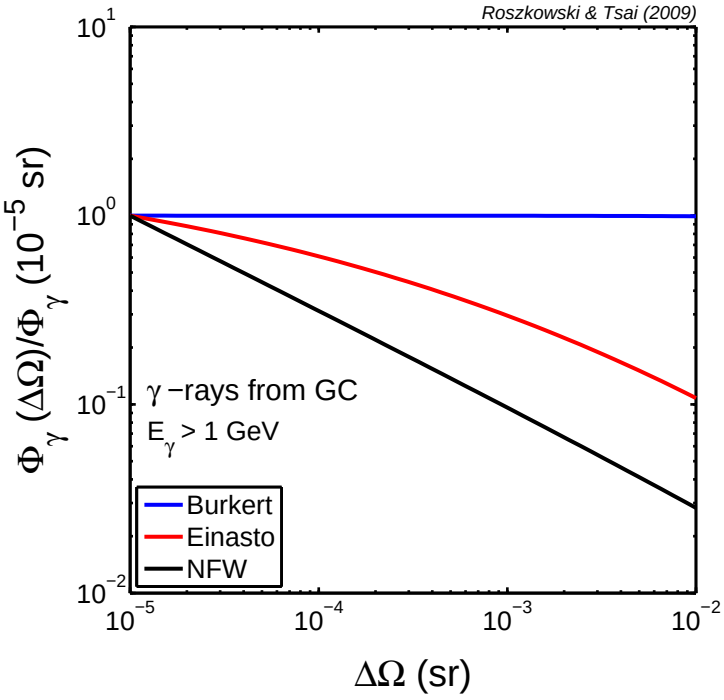

total flux

$$\Phi_\gamma(\Delta\Omega) = \int_{E_{\rm th}}^{m_X} dE_\gamma \frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\Omega)$$

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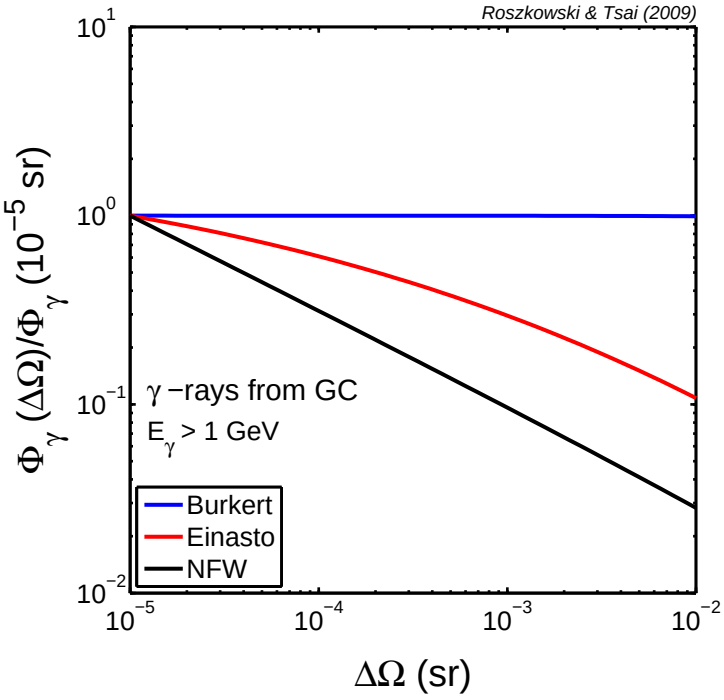
- data $\Rightarrow$ can get handle on DM halo density slope in GC

Tests of DM in the Galactic Center

enhance signal by integrating over energy and solid angle

arXiv:0909.1529



total flux

$$\Phi_\gamma(\Delta\Omega) = \int_{E_{\rm th}}^{m_X} dE_\gamma \frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\Omega)$$

Signal of DM if:

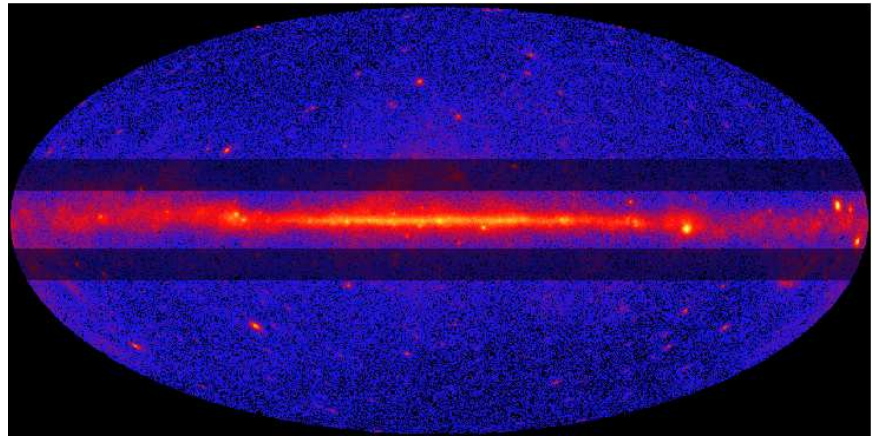
- data follows one of the curves
- data $\Rightarrow$ can get handle on DM halo density slope in GC

$\Rightarrow$ would provide an unambiguous signal of DM origin

Fermi LAT mid-latitude data

diffuse γ-rays from $10^\circ \leq |b| \leq 20^\circ$ and $0 \leq l < 360^\circ$, $0.1\,\mathrm{GeV} \leq E_\gamma \leq 10\,\mathrm{GeV}$

Porter, ICRC, 0907.0294



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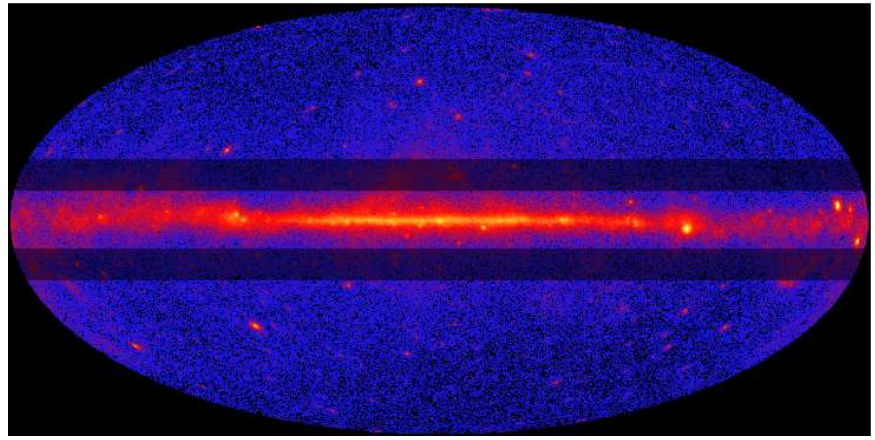

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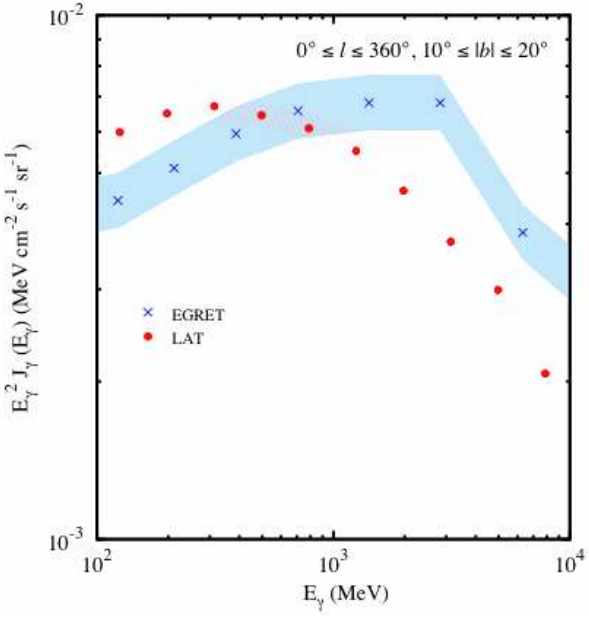

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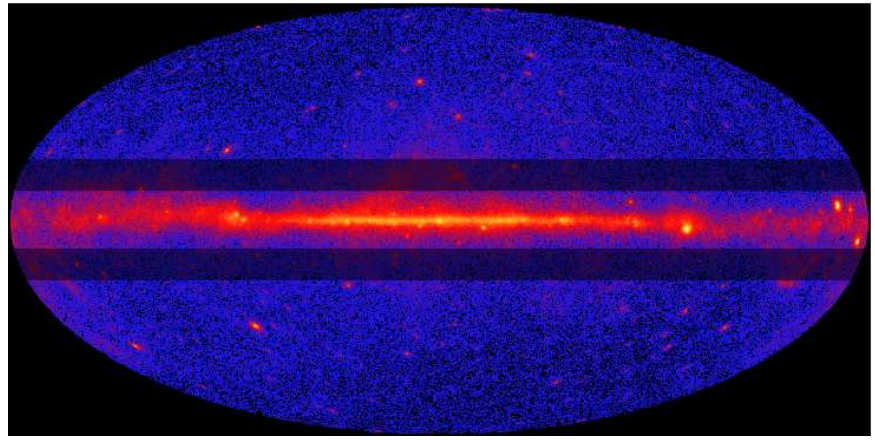

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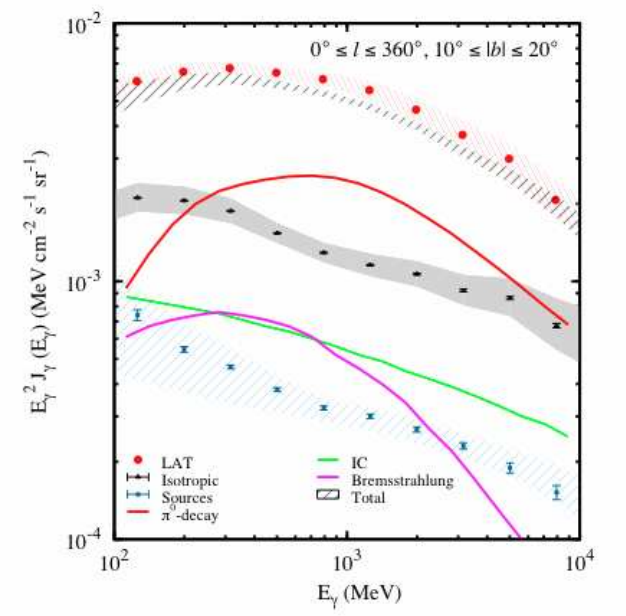

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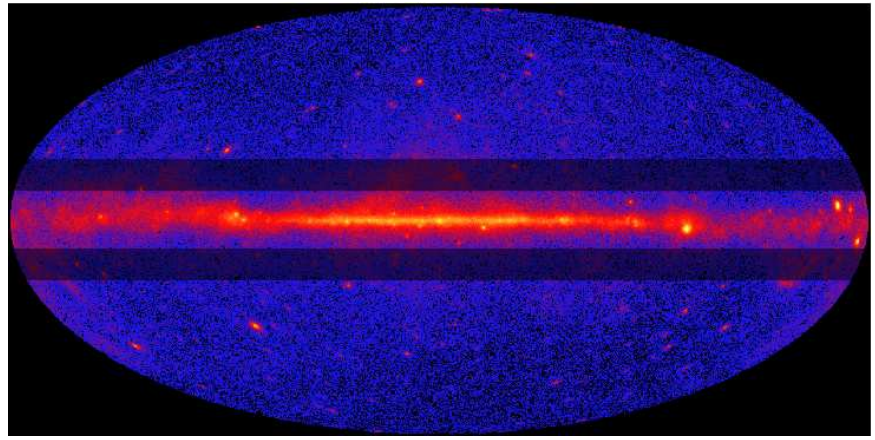

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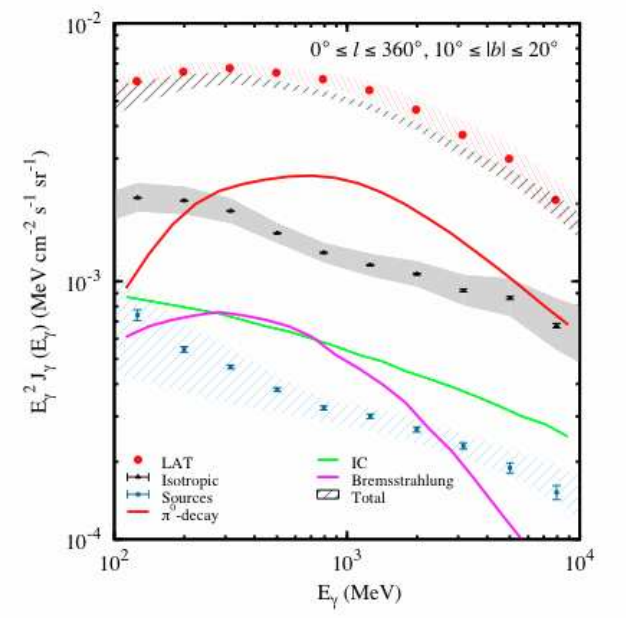

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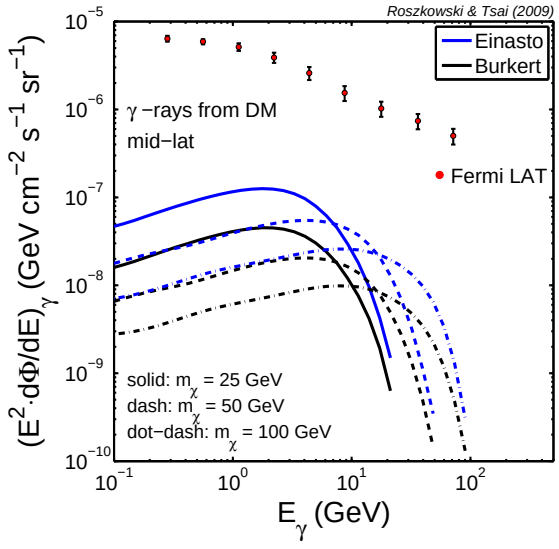

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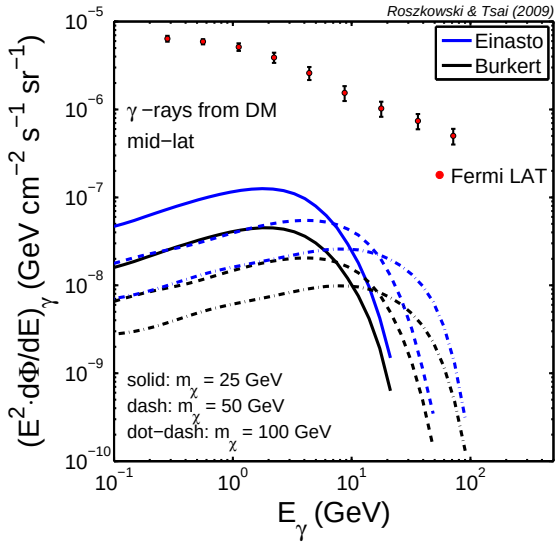

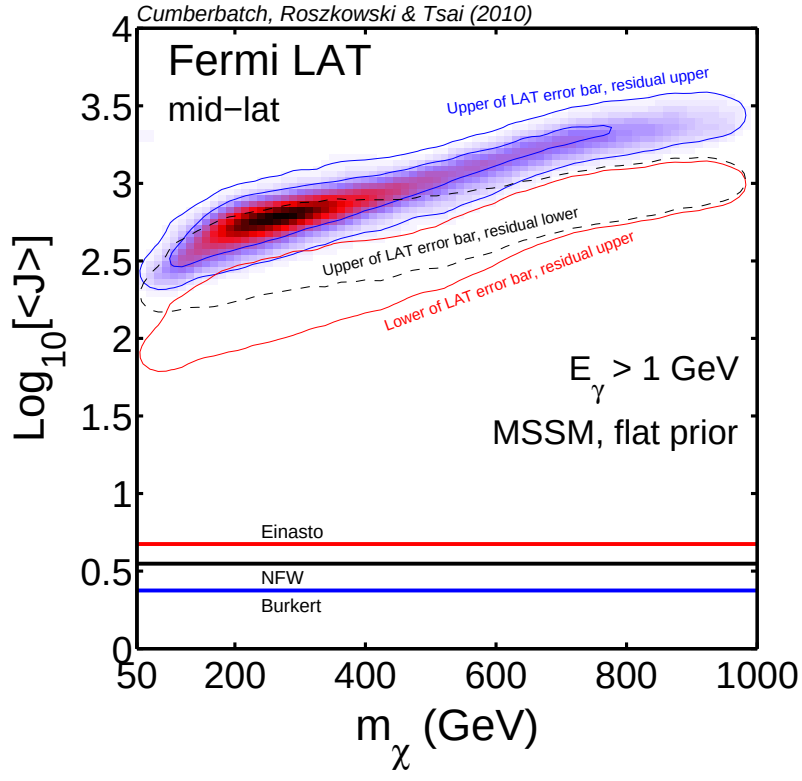

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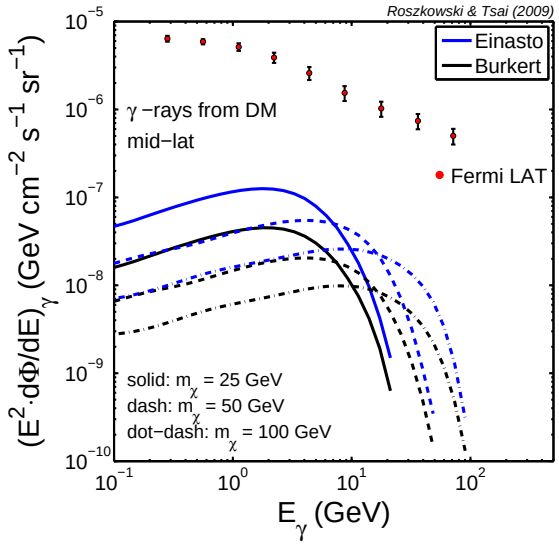

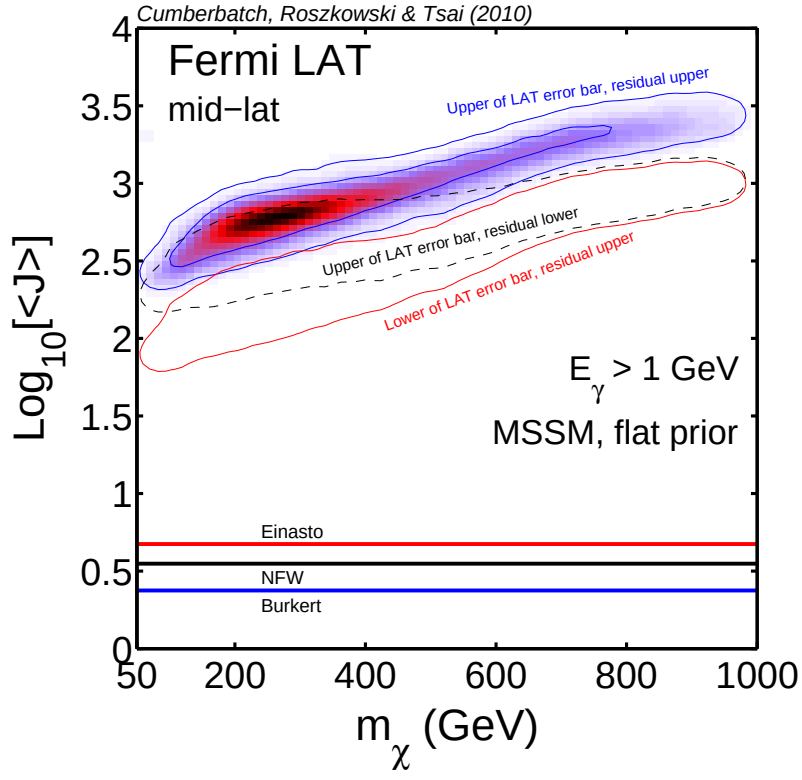

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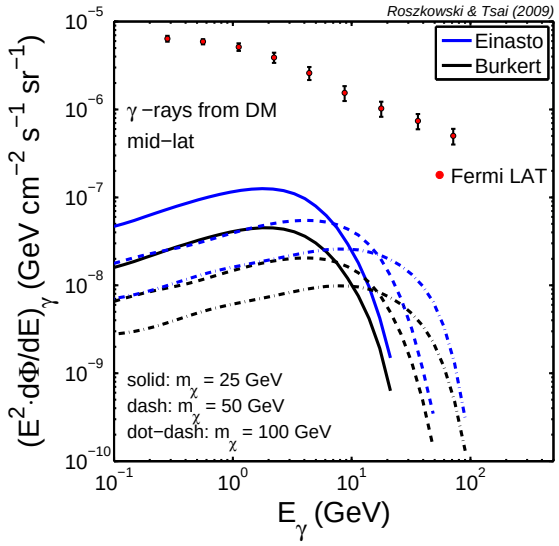

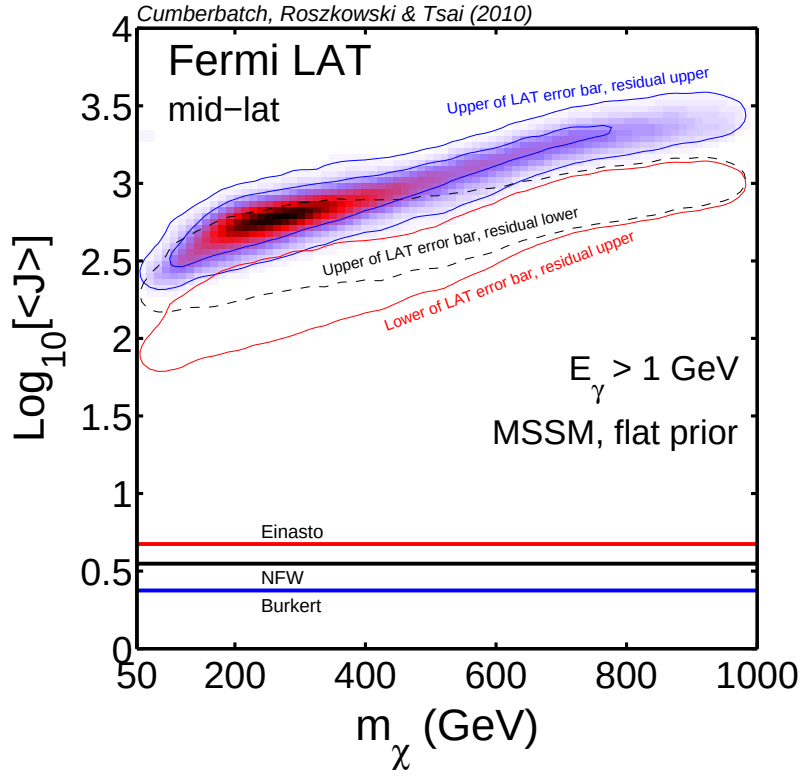

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still weak. Can be improved with GC data?

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