# The Lightest Higgs Boson and Relic Neutralino in the MSSM with CP Violation

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(based on: J. S. Lee, S. S., PRD75, 075001 (2007))

SUSY '07, Karlsruhe, Germany

# Introduction

• effective, minimal supersymmetric extension of the standard model with all soft parameters fixed at the Electro-Weak scale
• CP violating phases in the soft terms
• non universality of gaugino masses at the GUT scale

→ light Higgs and light neutralino allowed by accelerator searches

well defined region of the parameter space (CPX scenario)

what about Cosmology?

# The SUSY Higgs sector & CP violation

In presence of phases the 3 neutral mass eigenstates have no longer definite CP parities → mixing between scalar and pseudoscalar Higgs bosons:

$$(\phi_1, \phi_2, a)^T = O(H_1, H_2, H_3)^T$$

$\varphi_1$, $\varphi_2$ ,a : CP eigenstates

$H_1$ ,$H_2$ , $H_3$ : mass eigenstates ( $M_{H_1} < M_{H_2} < M_{H_3}$)

O: mixing matrix

$O\varphi_1 i$, $O\varphi_2 i$ = CP-even components } of i-th Higgs boson

$O_{ai}$ = CP-odd component } of i-th Higgs boson

The CP-violating mixing among neutral Higgs bosons is dominated by the contribution of squarks of the 3rd generation (largest Yukawas) and is proportional to the combination:

$$\frac{3}{16\pi^2}\frac{\Im\mathrm{m}(A_f\mu)}{m^2_{\tilde{f}_2} - m^2_{\tilde{f}_1}}$$

$A_f$=trilinear coupling

μ=Higgs-mixing parameter

$m_{\tilde{f}_i}$ = squark masses (i=1,2)

Higgs-boson couplings to SM and SUSY particles are modified. In particular the coupling to vector bosons becomes:

$$\mathcal{L}_{HVV} = gM_W\left(W_\mu^+ W^{-\mu} + \frac{1}{2c_W^2} Z_\mu Z^\mu\right)\sum_{i=1}^{3} g_{H_iVV} H_i$$

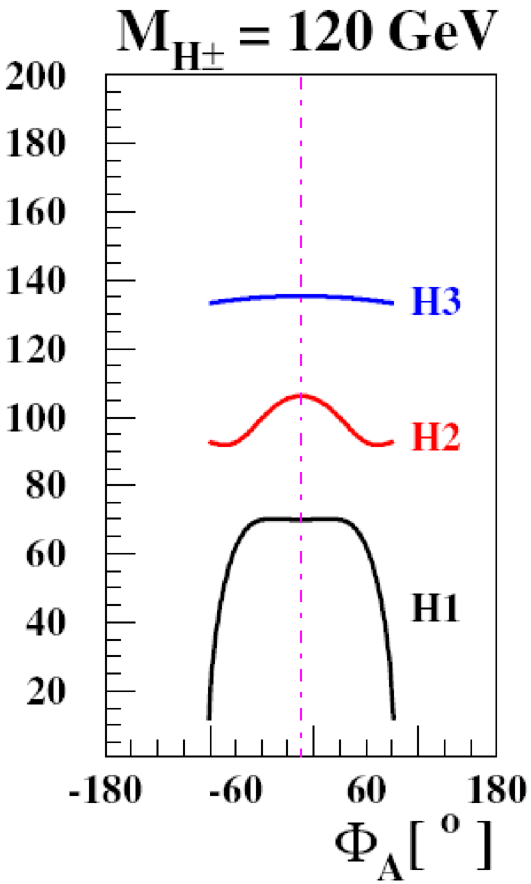
with:

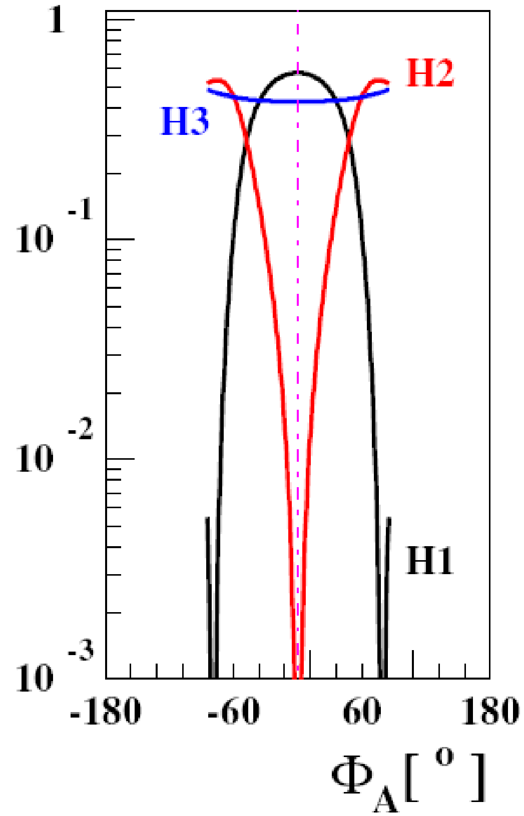
$$g_{H_iVV} = \cos\beta\, O_{\phi_1 i} + \sin\beta\, O_{\phi_2 i} \qquad (\tan\beta \equiv v_1/v_2)$$

N.B. : W,Z couple only to scalar components

➡ the coupling to i-th Higgs boson can be strongly suppressed if $H_i$ is mostly pseudoscalar, i.e. $|O_{ai}| \sim 1 >> |O_{\varphi_1 i}|, |O_{\varphi_2 i}|$

# The blind spot




masses

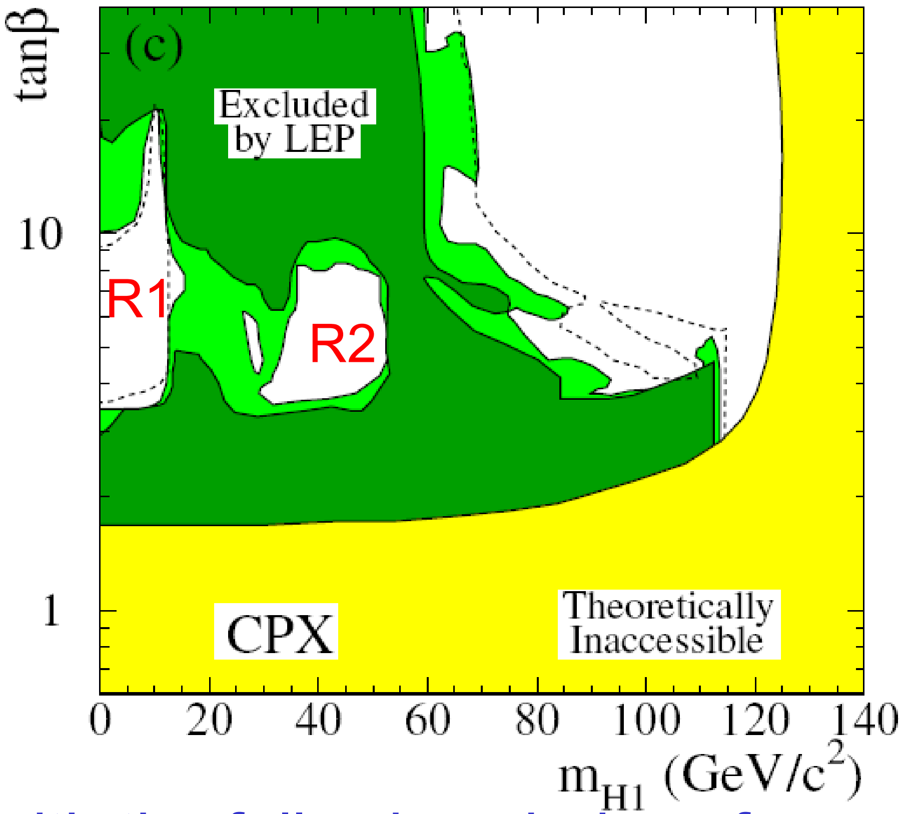
$g_{HVV}$ couplings

$H_1$ can be very light and almost decoupled from the Z

$H_2$ is close to the kinematic limit and mainly decays to $H_1H_1$

A very light Higgs boson could easily have escaped detection at LEP2

# Accelerator constraints on the Higgs mass




Two allowed regions for a light Higgs:

$$\mathbf{R1}: \quad M_{H_1} \lesssim 10 \;\; \mathrm{GeV}$$
$$\text{for} \;\; 3 \lesssim \tan\beta \lesssim 10$$

$$\mathbf{R2}: \quad 30 \;\; \mathrm{GeV} \lesssim M_{H_1} \lesssim 50 \;\; \mathrm{GeV}$$
$$\text{for} \;\; 3 \lesssim \tan\beta \lesssim 10$$

with the following choice of parameters (CPX benchmark):

$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\mathrm{SUSY}} = 0.5\,\mathrm{TeV}\,,$$

$$|\mu| = 4\,M_{\mathrm{SUSY}}\,, \quad |A_{t,b,\tau}| = 2\,M_{\mathrm{SUSY}}\,, \quad |M_3| = 1 \;\; \mathrm{TeV}$$

$$\Phi_3 \equiv \mathrm{Arg}(M_3) = \Phi_A \equiv \mathrm{Arg}(A_t) = \mathrm{Arg}(A_b) = \mathrm{Arg}(A_\tau) = 90^\circ$$

We assume without loss of generality the convention arg(μ)=0

# The neutralino

Defined as usual as:

$$\chi \equiv a_1 \tilde{B} + a_2 \tilde{W}^{(3)} + a_3 \tilde{H}_1^0 + a_4 \tilde{H}_2^0$$

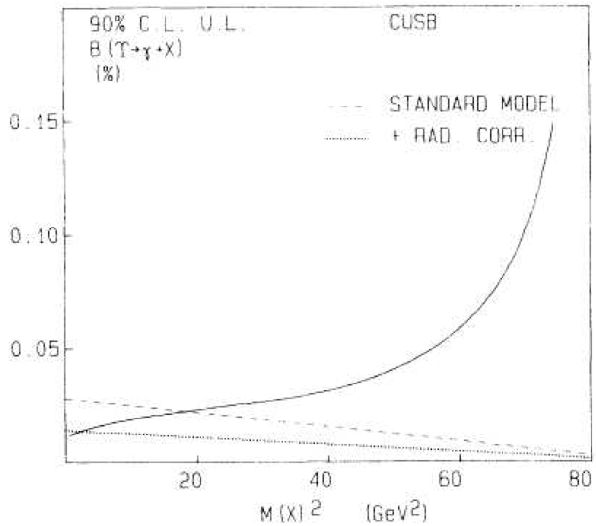
- we assume R parity conservation, so that the neutralino is a Dark Matter candidate
- we relax the GUT relation among gaugino masses, taking $|M_1| << |M_2|$
- in this case the neutralino can be light, becouse its mass $m_\chi$ is not constrained by chargino searches at LEP
- in the CP conserving case the lower bound is obtained from cosmology, $m_\chi > 7$ GeV (Bottino, Fornengo, Scopel, PRD67,063519 (2003))
- we assume $\arg(M_1) = \arg(M_2) = 0$, $M_2 = 200$ GeV (the phenomenology of the lightest neutralino is not sensitive to this choice)

we relay for the computation of masses and couplings on the code CPsuperH ( J. S. Lee, A. Pilaftsis, M. Carena, S. Y. Choi, M. Drees, J. R. Ellis and C. E. M. Wagner, Comput. Phys. Commun. 156, 283 (2004))

Additional constraints on $M_{H_1}$ :

- atomic EDM of $^{205}$Tl (2-loop contribution from 3$^{rd}$ family squarks + contribution from first and second generation phases): $|d_{Tl}|<1.3 \times 10^{-24}$ [e cm]
- bottomonium decay:

$$B(\Upsilon(1S) \to \gamma\, H_1)_{SUSY} \simeq B(\Upsilon(1S) \to \gamma\, H_1)_{SM} \times (O_{a1} \tan\beta)^2$$




- BR($B_S \to \mu\mu$)<1 x $10^{-7}$ : $B(B_s \to \mu\mu) \simeq \frac{2\,\tau_{B_s} M_{B_s}^5 f_{B_s}^2}{64\pi} |C|^2 (O_{\phi_1 1}^4 + O_{a1}^4)$

$$C \equiv \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left(\frac{\tan^3\beta}{4\sin^2\theta_W}\right) \left[\frac{m_\mu\, m_t\, |\mu|}{M_W^2 (M_{H_1}^2 - M_{B_s}^2)}\right] \left(\frac{\sin 2\theta_{\tilde{t}}}{2}\right) \Delta f_3$$

+squarks of first 2 families

# Additional constraints on $M_{H_1}$:

Allowed region:

enlarged to:

$7 \text{ GeV} \lesssim M_{H_1} \lesssim 10 \text{ GeV}$

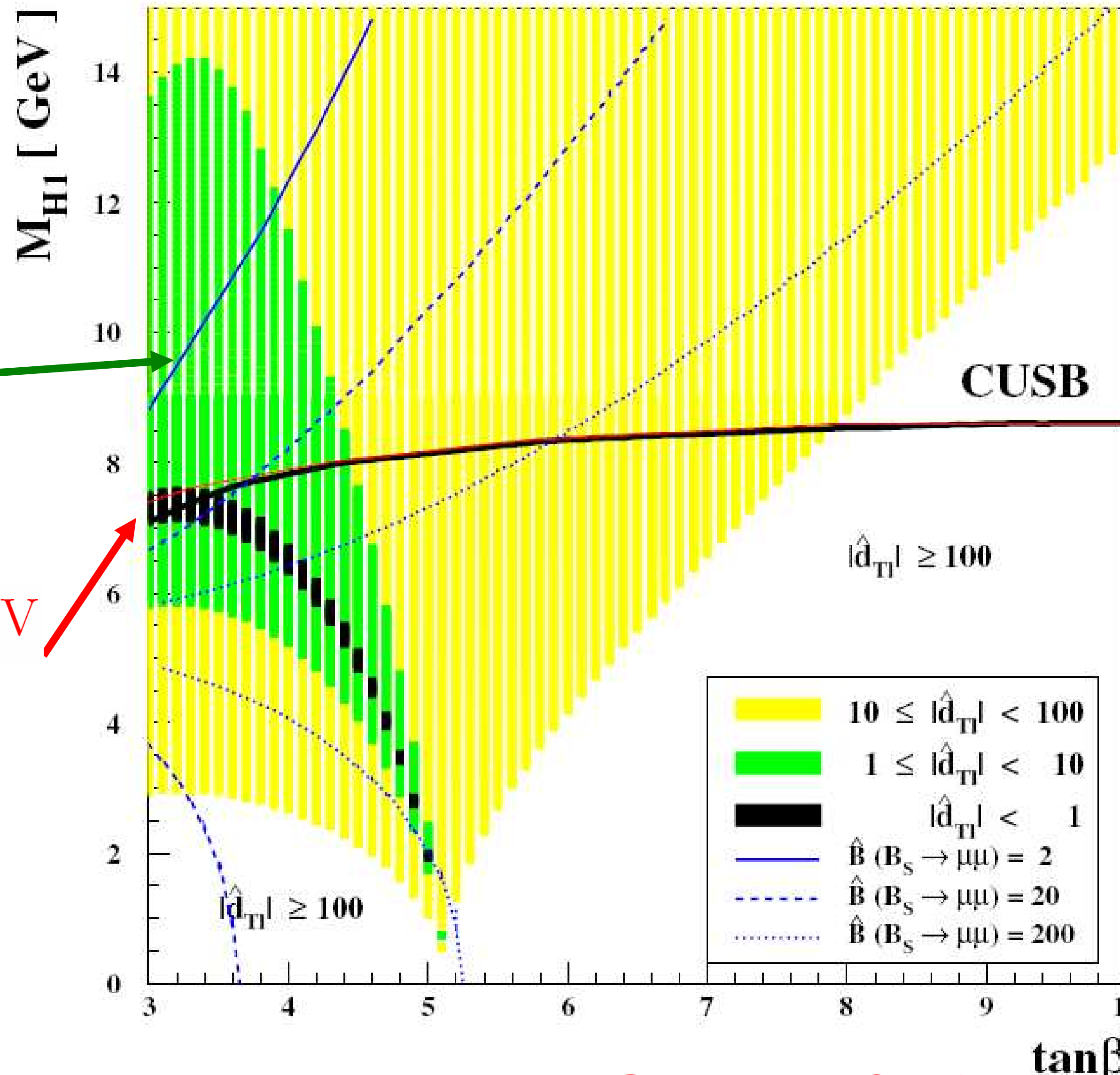
and $3 \lesssim \tan\beta \lesssim 5$

when allowing 10% cancellation in Tl EDM

$7 \text{ GeV} \lesssim M_{H_1} \lesssim 7.5 \text{ GeV}$

and $\tan\beta \simeq 3$

Also cancellation due to "GIM operative point" in $B_S \to \mu\mu$ (Dedes, Pfilatsis, PRD67,015012(2003))




in the following we will take: $M_H$=7.5 GeV, tan β =3

Other constraints:

- invisible with of Z boson
- BR(b→s γ ) (assuming MFV)
- muon anomalous magnetic moment

are less severe.

This is mainly due to the fact the in the CPX scenario tanβ is small and the lighest neutralino is a very pure Bino ($M_1 << M_2$) with a small Higgsino component:

$$\frac{|a_3|}{|a_1|} \simeq \sin\theta_W \sin\beta \frac{M_Z}{\mu}$$

$\mu$=2 TeV>>$M_Z$ → $|a_3| << |a_1|$

important for relic neutralino phenomenology

# The relic density

From observation:

$$0.096 < \Omega_m h^2 < 0.122$$

If the neutralino is a thermal relic, the relic abundance depends on its annihilation cross section $\sigma_{ann}$ to SM particles:

$$\Omega_\chi h^2 = \frac{x_f}{g_\star (x_f)^{1/2}} \frac{3.3 \cdot 10^{-38}\ \mathrm{cm}^2}{\widetilde{\langle \sigma_{\mathrm{ann}} v \rangle}}$$

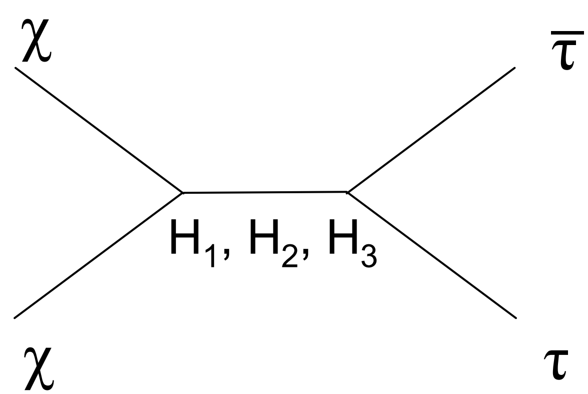
with: $\widetilde{\langle \sigma_{\mathrm{ann}} v \rangle} \equiv x_f \langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{int}}$ $\quad x_f \equiv \frac{m_\chi}{T_f}$

$$\langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{int}} \equiv \int_{T_0}^{T_f} \langle \sigma_{\mathrm{ann}} v \rangle dT / m_\chi$$

$$T_f \equiv \mathrm{decoupling\ temperature} \simeq m_\chi / 20$$

$g_*$= # of relativistic degrees of freedom at decoupling

However, for the CPX scenario the natural scale of $\Omega_\chi$ is too large compared to observation




In fact $\sigma_{ann}$ is too small. The dominant contribution (Higgs exchange) is suppressed since:

- tan $\beta$ is small
- neutralino-Higgs couplings are suppressed for a very pure Bino
- if $m_\chi < m_b$ annihilation to bottom quarks is not kinematically allowed

$\sigma_{ann}$ needs a boost → resonant annihilation when $m_\chi \approx M_H/2$

# Resonant annihilation through $H_1$ exchange

The annihilation cross section to the final state f can be derived from the relation (brackets=thermal average):

$$\langle \Gamma(\chi\chi \to f) \rangle = \langle \Gamma(\chi\chi \to H_1) B(H_1 \to f) \rangle$$

$$\frac{n_\chi^2}{2} \langle \sigma_{\rm ann} v \rangle_{{\rm res},f} \qquad\qquad n_{H_1} \Gamma_\chi \frac{K_1(x_{H_1})}{K_2(x_{H_1})} B_f$$

($x_i \equiv m_i / T$, $B_f$=branching ratio to f, $K_i$=Bessel functions)

$$< \sigma_{ann} v >_{\rm res} = \frac{\pi^2 M_{H_1}^2}{m_\chi^5} \frac{x_\chi K_1(x_{H_1})}{K_2^2(x_\chi)} \Gamma(H_1) B_\chi (1 - B_\chi) \Theta\left(\frac{x_{H_1}}{x_\chi} - 2\right)$$

Using the approximation, valid for z>>1:

$$K_1(z) \simeq K_2(z) \simeq \left(\frac{\pi}{2z}\right)^{1/2} \exp^{-z}$$

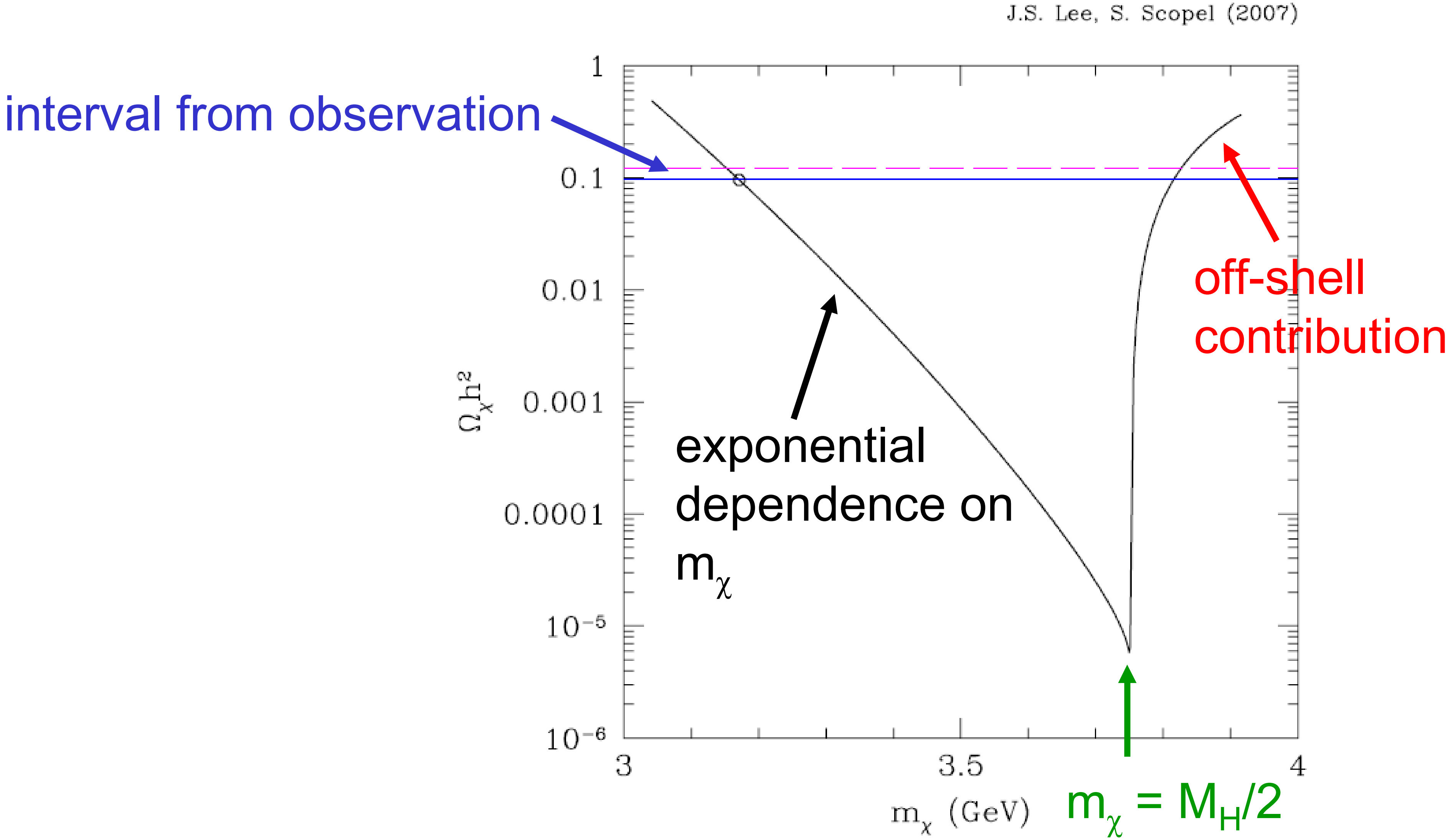
the integral over temperature can be done analytically, yielding:

$$< \widetilde{\sigma_{ann} v} >_{\rm res} \simeq 4\pi^2 \frac{x_f \Gamma(H_1)}{m_\chi^3} \frac{B_\chi(1-B_\chi)}{\beta_\chi} \sqrt{\frac{\delta(\delta+1)}{2}} \left[1 - erf\left(\sqrt{2(\delta-1)x_f}\right)\right]$$

$$\delta \equiv \frac{M_{H_1}}{2m_\chi}$$

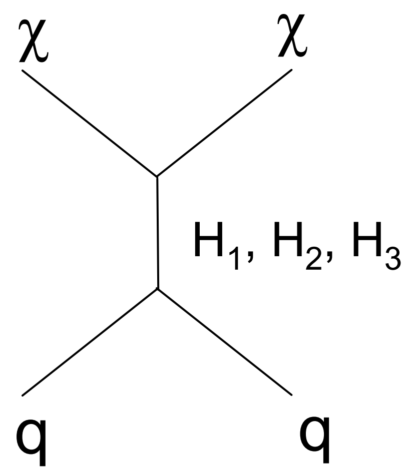
very sensitive to the neutralino mass

# The relic abudance




asymmetric shape: thermal motion allows resonant annihilation for $m_\chi < M_H/2$, while this is not possible for $m_\chi > M_H/2$

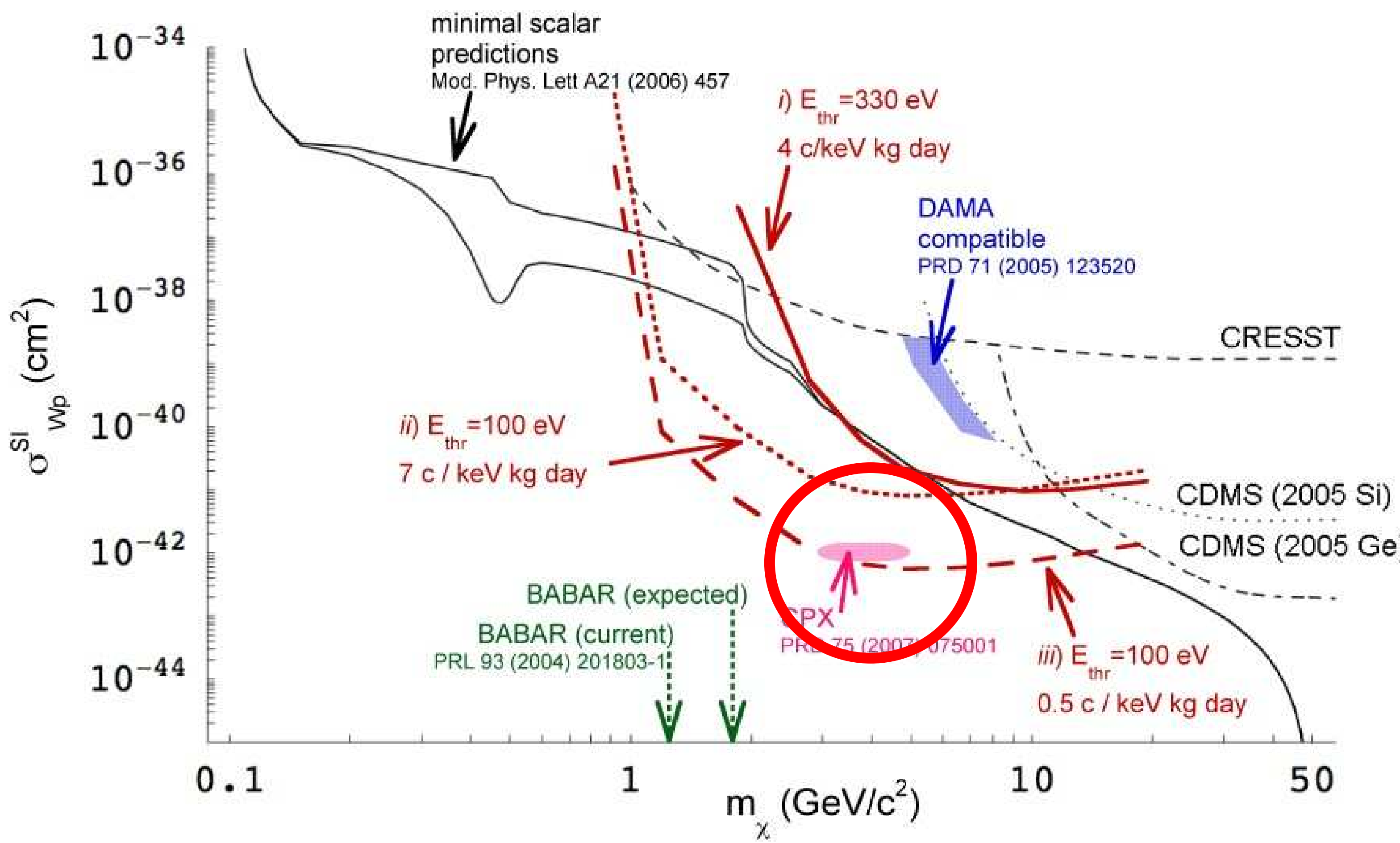
# Direct searches (neutralino-nucleus elastic scattering)




Although $H_1$ is light, the cross section is strongly suppressed, since:

- small tan $\beta$
- very pure Bino (H-$\chi$ coupling suppressed)
- non-relativistic $\chi$ 's in the lab frame → elastic cross section is dominated by the exchange of scalars, while $H_1$ is mostly pseudoscalar
- no resonant enhancement in propagator (t-channel)

very hard to detect: sub-keV threshold and sizeable detector mass needed. Proposed strategy: a new type of low-capacity germanium diode (P. S. Barbeau, J. I. Collar, O. Tench, nucl-ex/0701012):

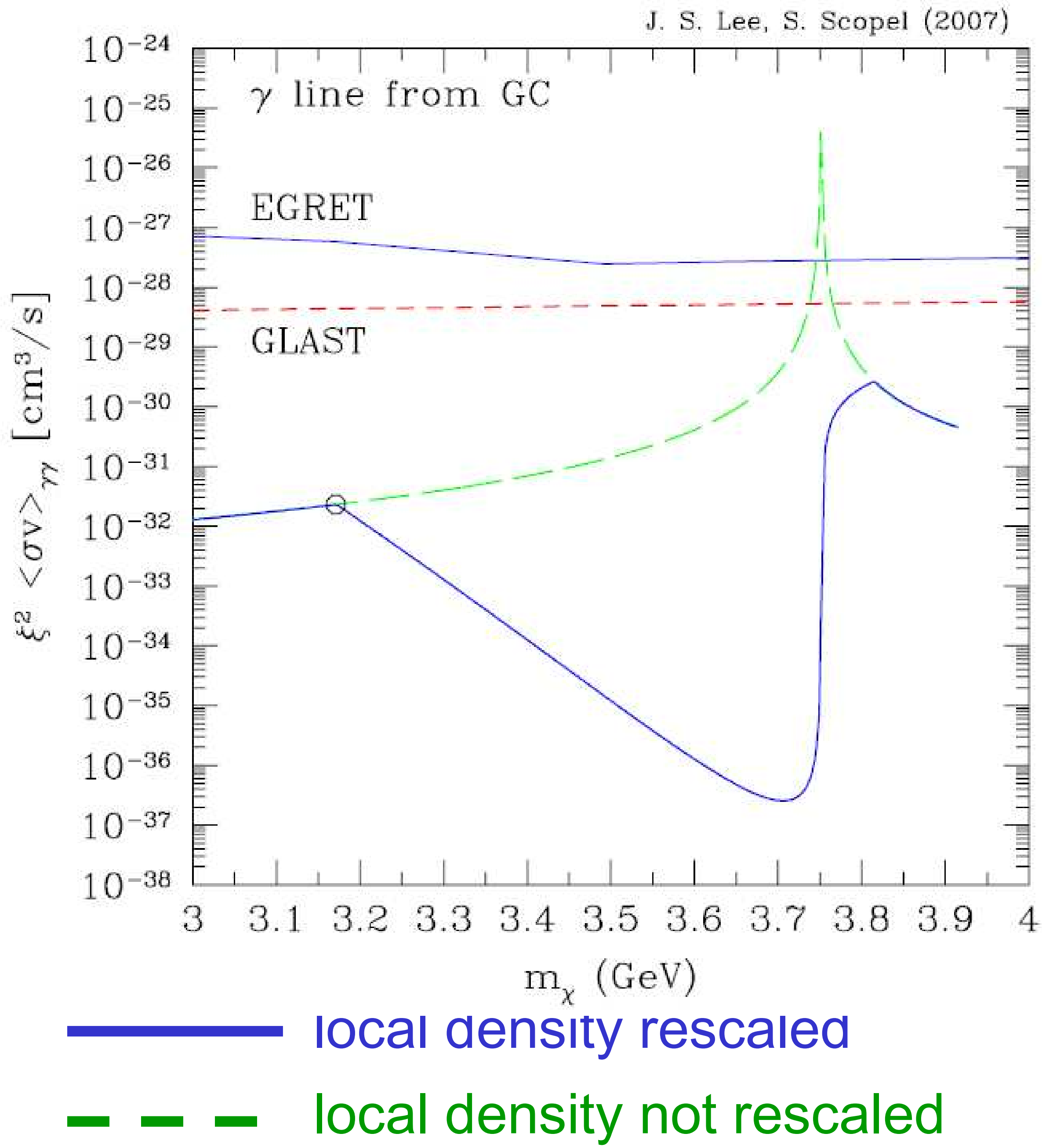


# Indirect searches

- relic density driven below observational limit by the annihilation cross section $<\sigma_{ann}v>$ in the early Universe
- same cross section at present times $<\sigma_{ann}v>_0$ enters into the calculation of the annihilation rate of neutralinos in our Galaxy
- signals: $\gamma$'s, $\nu$'s, exotic component in cosmic rays like antiprotons, positrons, antideuterons
- in the early Universe when $m_\chi < M_H/2$ the resonance can be accessible due to thermal motion, while at present times this is not true because the temperature is much lower
- one can have $<\sigma_{ann}v>_0 << <\sigma_{ann}v>$, so the annihilation cross section can be large enought in the early Universe in order to provide the correct relic abundance, but not so large at present times as to drive indirect signals beyond observational limits

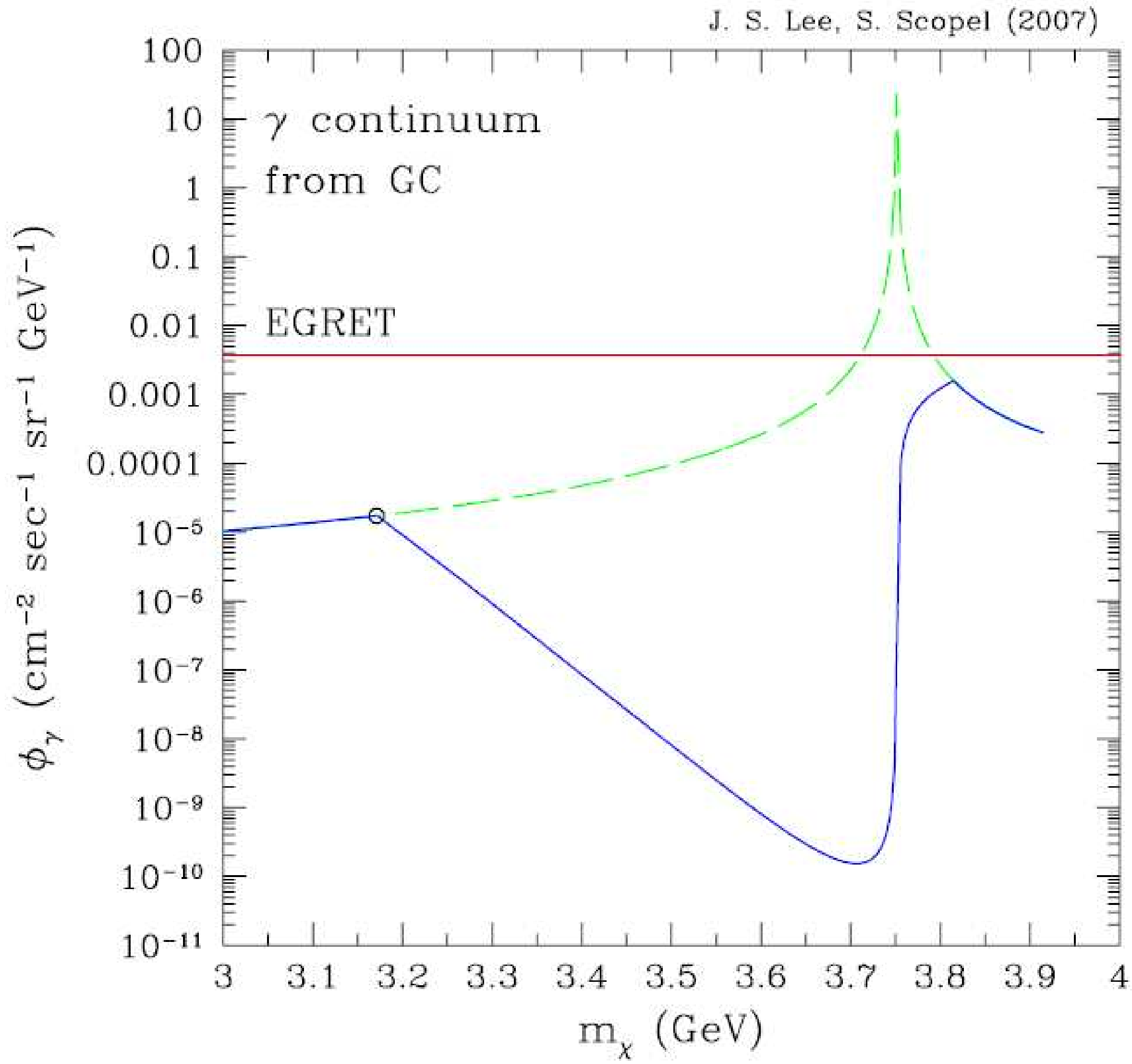
# Gamma flux from the galactic center: line

NFW density profile
$r_{cut}=10^{-2}$ pc



# Gamma flux from the galactic center: continuum

NFW density profile
$r_{cut}=10^{-2}$ pc

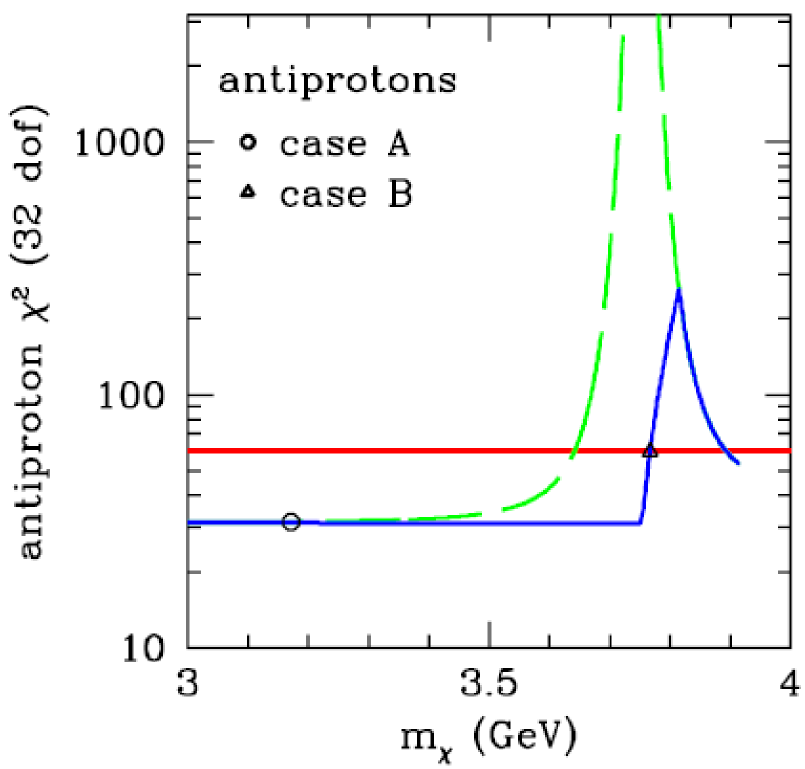



local density rescaled

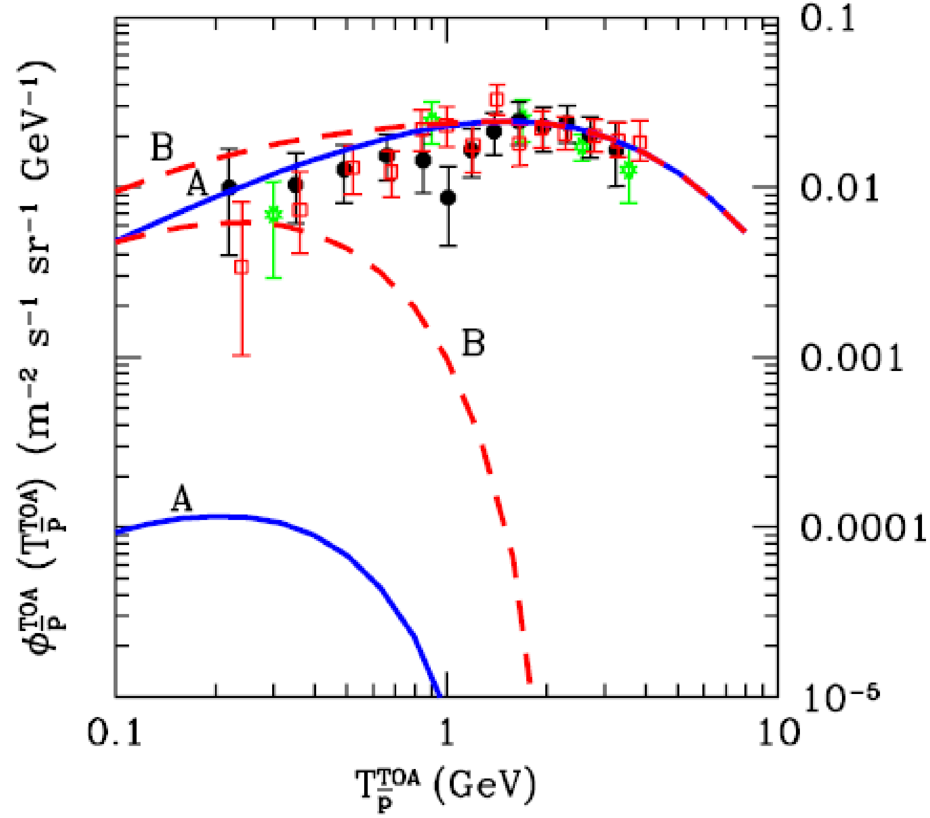
local density not rescaled

# Top-of-atmosphere antiproton flux

$\chi^2$ of signal compared to data




J. S. Lee, S. Scopel (2007)



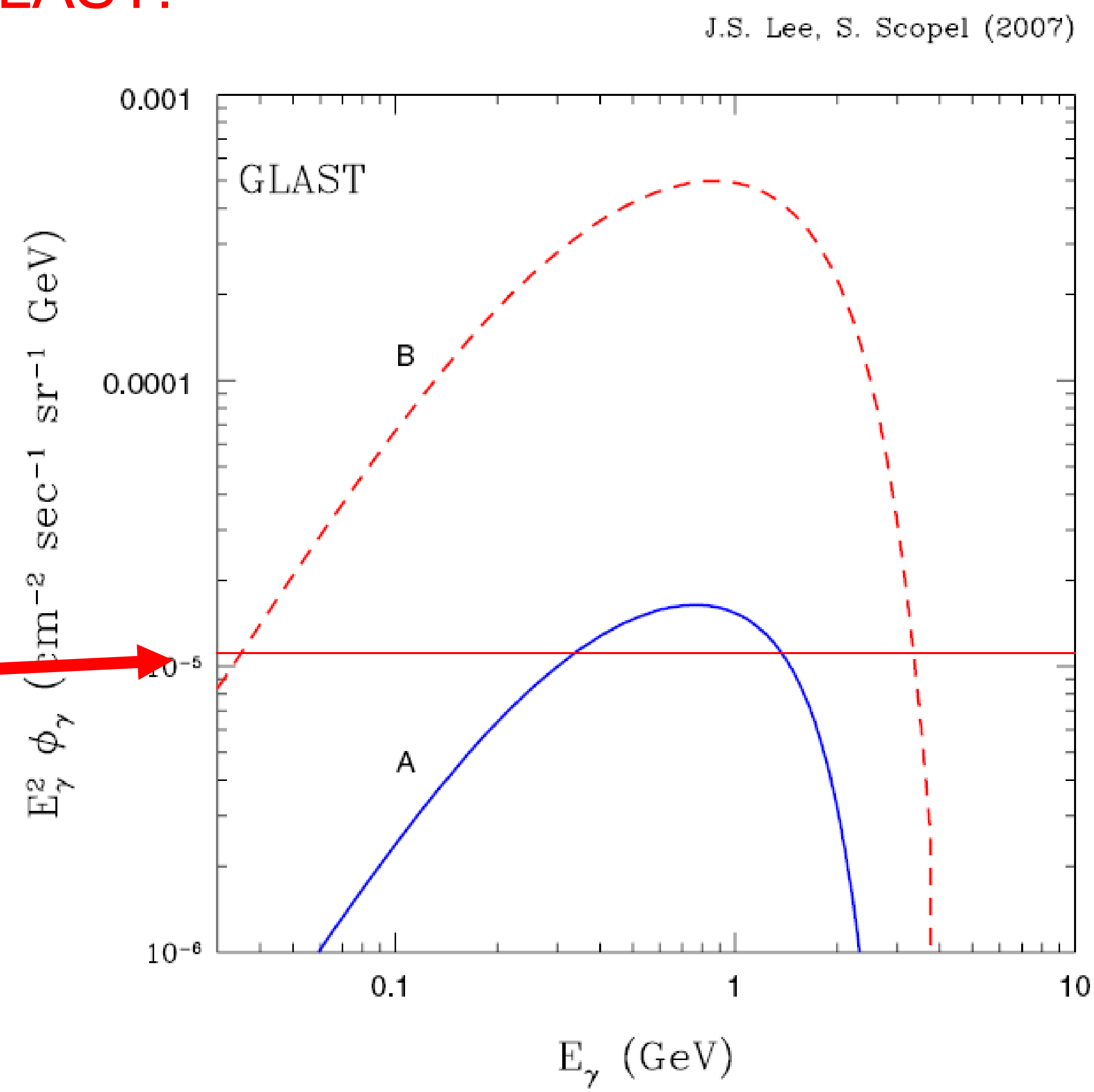

local density rescaled

local density not rescaled

Cases A and B correspond to the boundary of allowed mass range

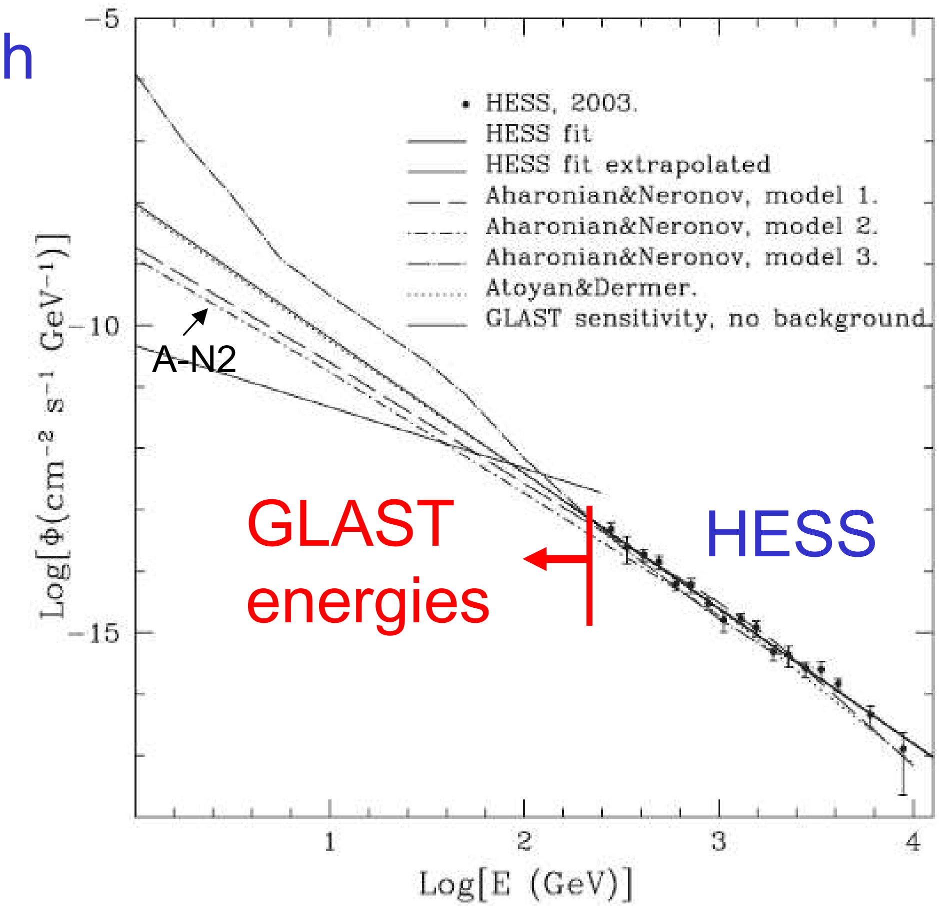
Expected signal for GLAST:

expected sensitivity obtained extrapolating background measured at higher energies by HESS
(optimistic model A-N2, Zaharias, Hooper, PRD73,103501 (2006))



Zaharias, Hooper, PRD73,103501 (2006)

HESS data, TeV source with constant slope power spectrum dN/dE α $E^{-2.2}$
quite different from what expected from Dark Matter (changing slope)
very hard spectrum, $m_\chi$ >>1 TeV needed
HESS flux extrapolated to lower energies is a background for GLAST



# Conclusions

- the combination of experimental constraints from Thallium EDM, quarkonium decays and $B_S \to \mu\mu$ restricts the low-Higgs mass region allowed by LEP to: 7 GeV < $M_H$<7.5 GeV, tanβ=3
- enlarged to 7 GeV < MH<10 GeV, 3<tanβ<5 allowing for 10 % cancellation in Th EDM between two-loop contribution and those depending on first- and second-generation phases
- through resonant annihilation via $H_1$ s-channel exchange, neutralinos with 3 GeV <$m_\chi$<5 GeV can be viable DM candidates, compatible to constraints coming from present DM searches
- tuned scenario. A similar situation happens in SUGRA (stau coannihilation, Higgs funnel and focus point)
- some analogies with the NMSSN scenario (Ferrer, Krauss, Profumo, PRD74,115007(2006); Gunion, Hooper, McElrath, PRD73,015011(2006); Demisek, Gunion, McElrath, hep-ph/0612031)