The interplay between dark matter searches and SUSY observables at LHC

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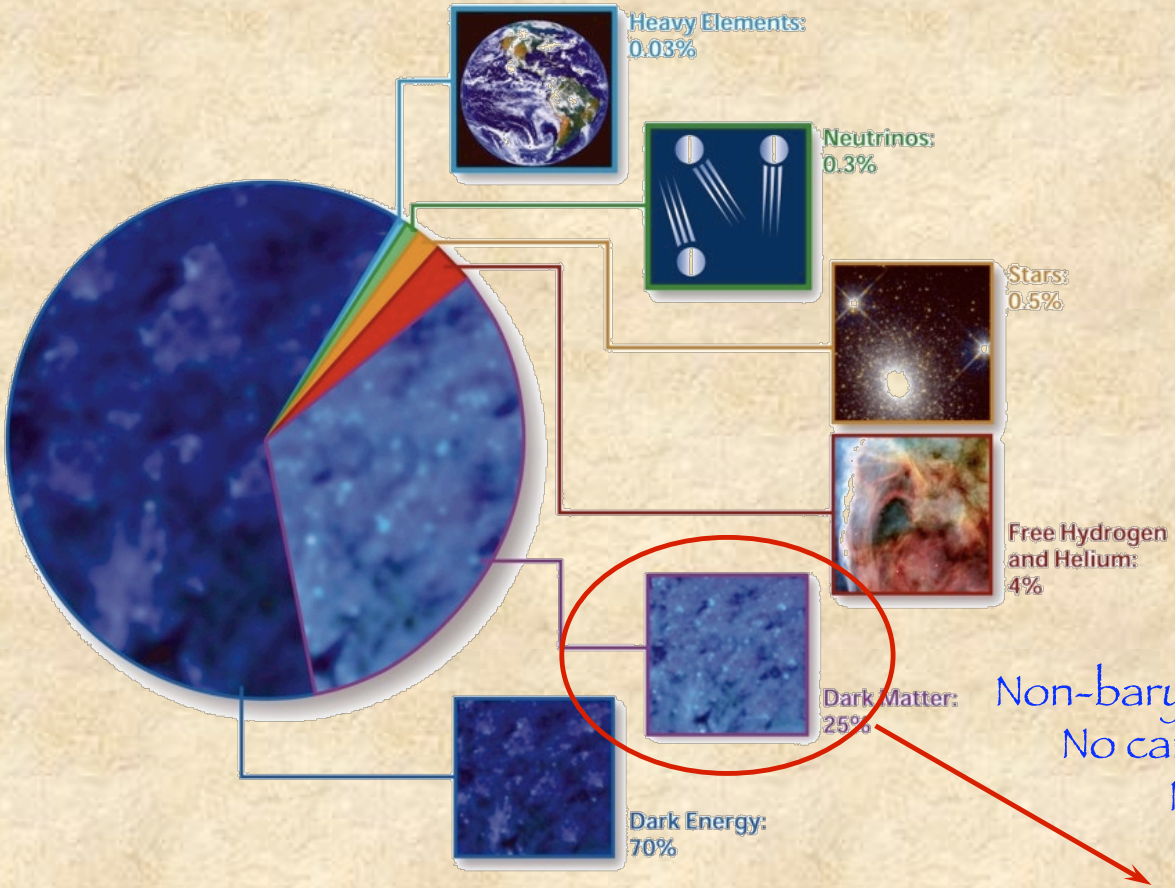
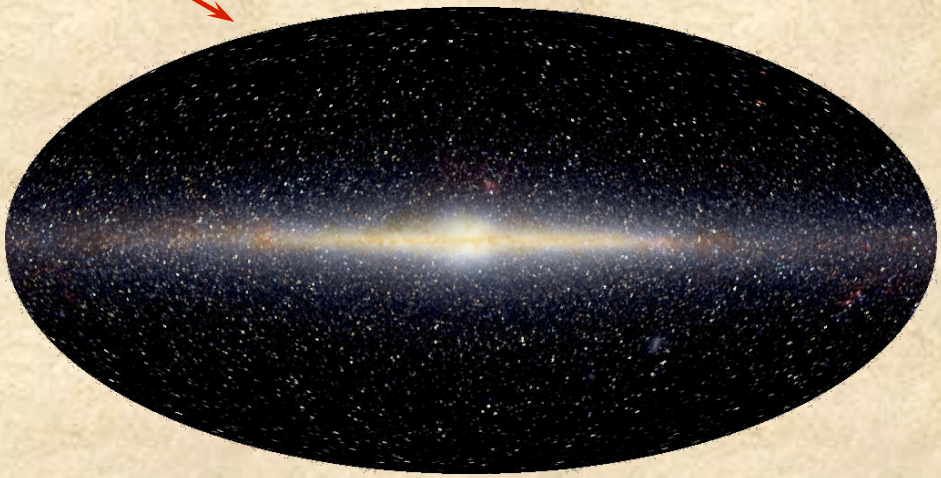
INFN Torino

PROMETEO I: LHC Physics and Cosmology
Department of Theoretical Physics, University of Valencia, 05.03.2009

Dark Matter



Non-baryonic (cold) dark matter is needed
No candidate in the Standard Model
New fundamental Physics



Dynamics of galaxy clusters
Rotational curves of galaxies
Weak lensing
Structure formation from primordial density fluctuations
Energy density budget

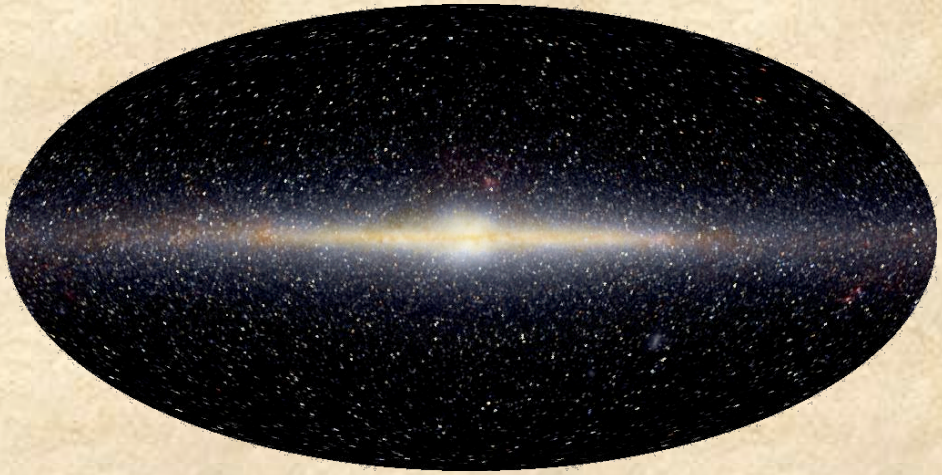
Galactic Dark Matter

CDM in galaxies:

- Massive particle with weak-type interactions (WIMP)
- Distributed to form a halo
  - Thermal component
  - Substructures
  - Non-thermal component

Galactic dark matter detection:

- Identify types of signals
- Exploit specific signatures
- Study relevant backgrounds
- Quantify uncertainties



MultiChannel search of dark matter

- Direct search: elastic scattering of χ off nuclei in a low background detector
  - → recoil energy of the nucleus
  - annual modulation of the rate
  - directionality of the recoil
- Indirect searches:
  - signals due to $\chi\chi$ annihilation taking place inside celestial bodies (Sun, Earth) where χ have been captured and accumulated
    - → Neutrino flux → up-going muons in a neutrino telescope
      - source location/some spectral feature
  - signals due to $\chi\chi$ annihilation taking place in the galactic halo
    - → Neutrinos — source location/some spectral feature
    - → Photons
      - ~ continuous gamma-ray flux — source location/some spectral feature
      - ~ gamma-ray line — very good spectral feature
    - → Positrons — spectral feature
    - → Antiprotons — spectral feature
    - → Antideuterons — very good spectral feature
    - → Electrons/positrons → multiwavelength search (radio, X, gamma rays; SZ on CMB)

Hints of a signal?

- Direct detection: DAMA annual modulation of the rate

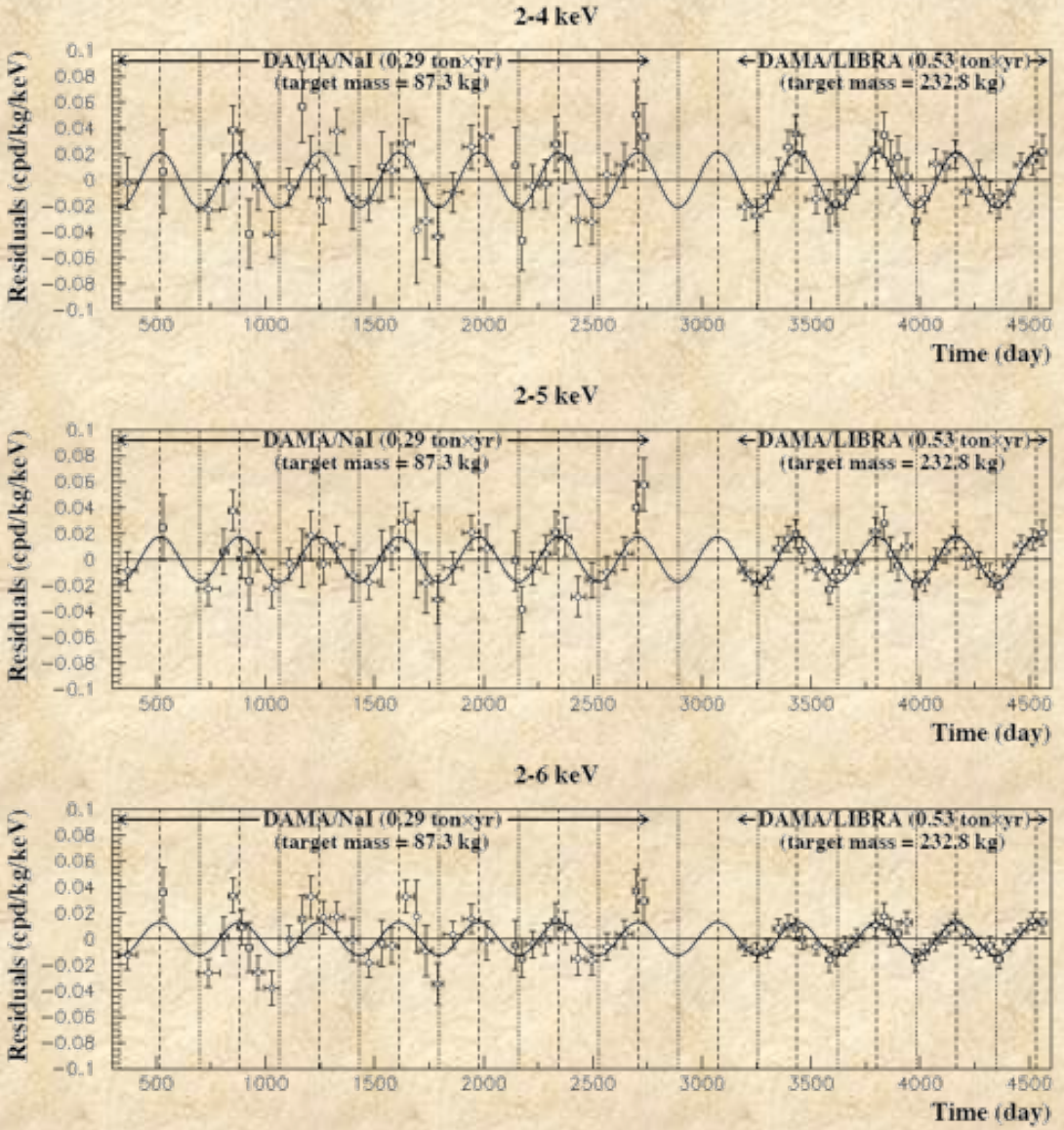
DAMA annual modulation

Effect at 8.2 σ C.L.

No known source of background

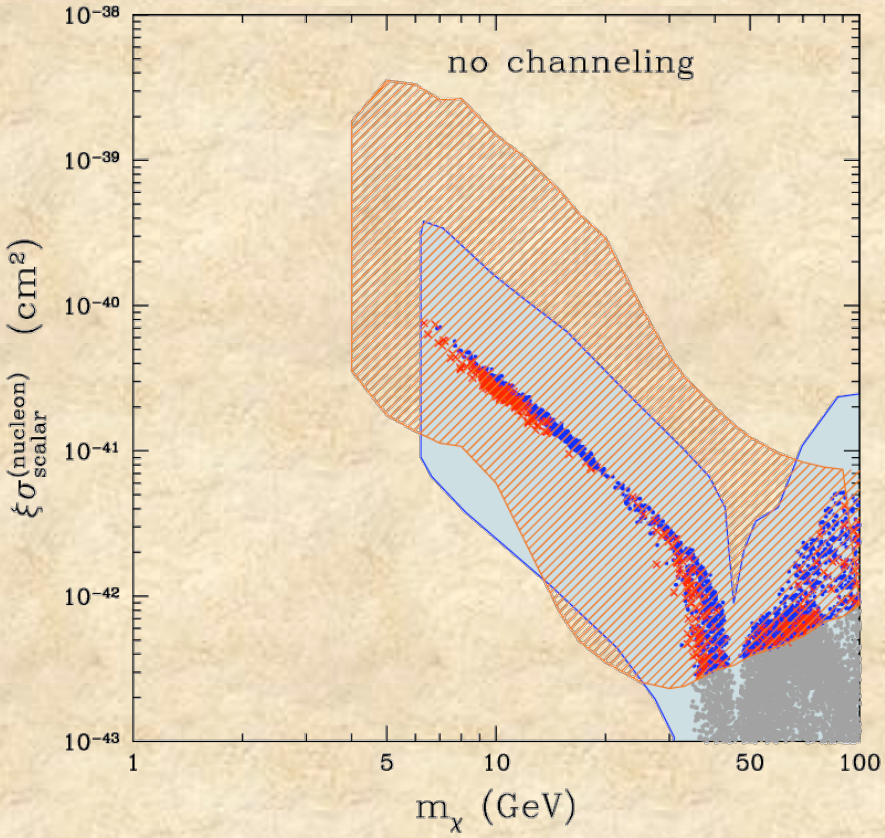
Stability parameters do not modulate

May be due to DM scatter
- off nuclei
- on electrons



R. Bernabei et al., Eur.Phys.J.C56 (2008) 333

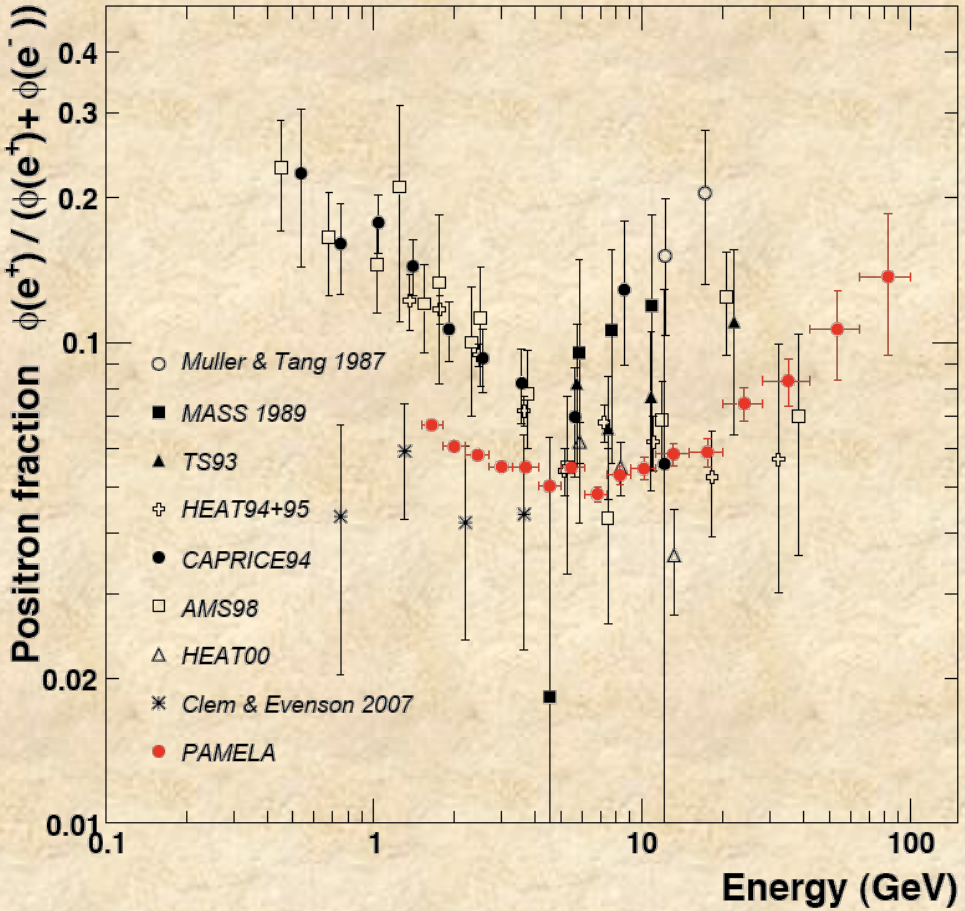
Direct detection: DAMA annual modulation



Hints of a signal ?

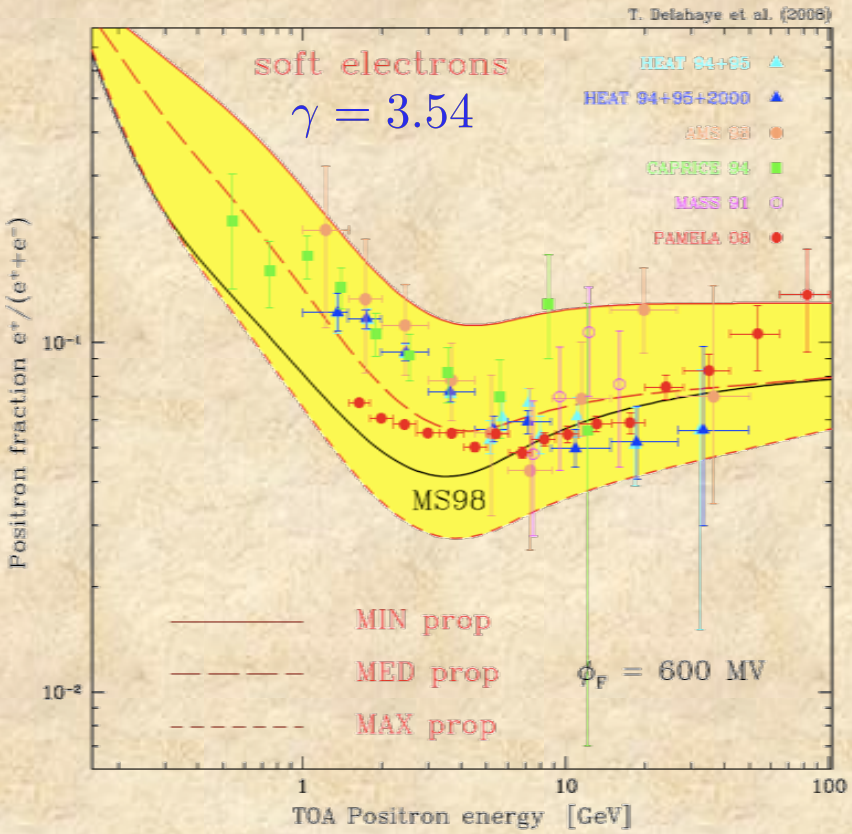
- Direct detection: DAMA annual modulation of the rate
- Leptons: PAMELA positron fraction [ATIC ?]

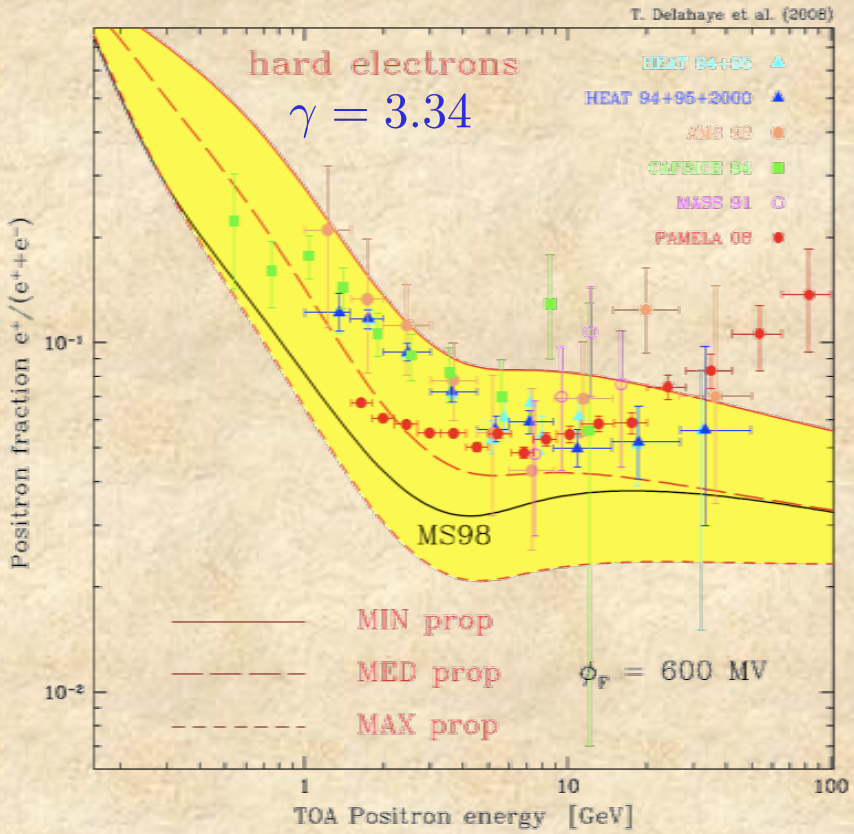
PAMELA positron fraction



O. Adriani et al. (PAMELA Collab.), arXiv:0810.9995 [astro-ph]

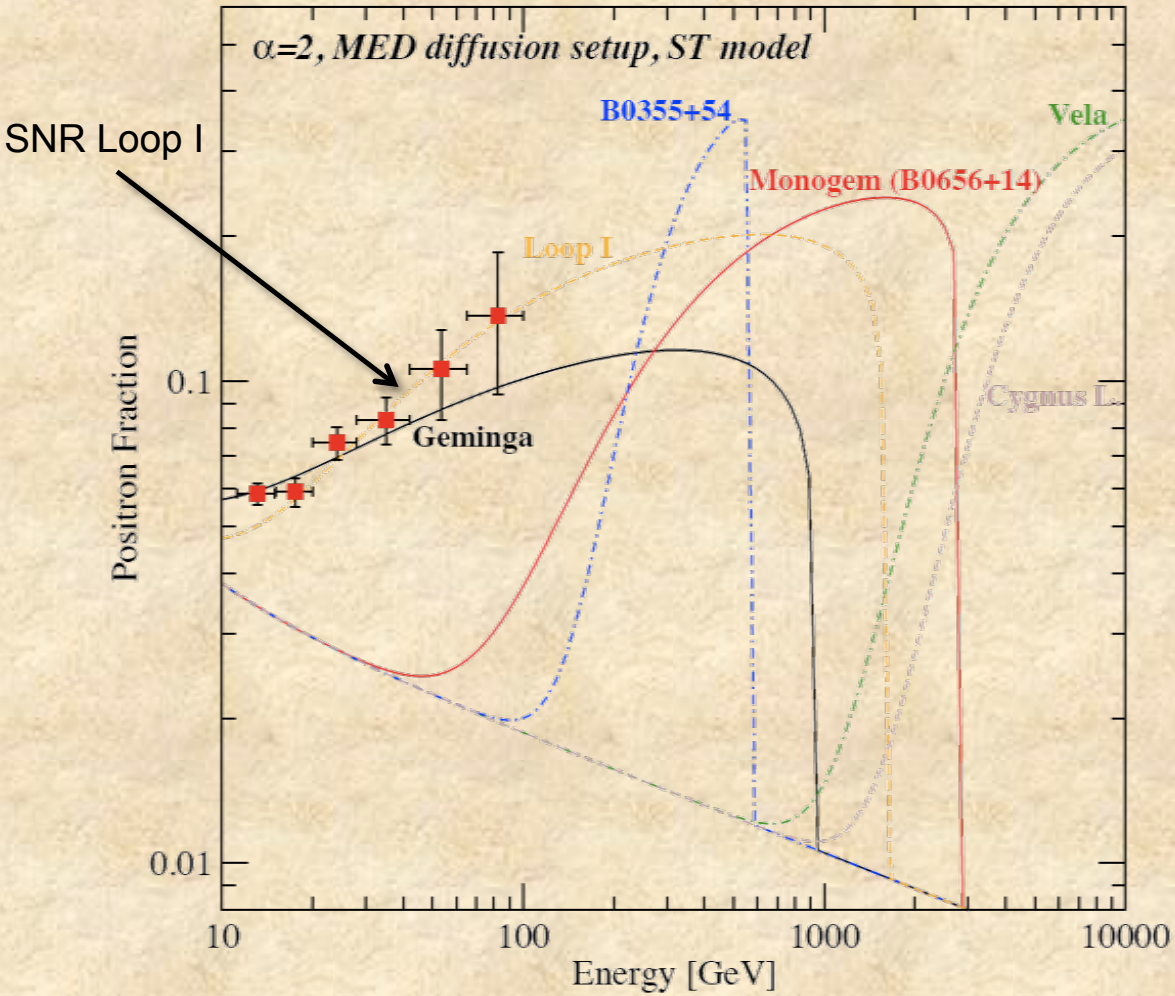
Positron fraction: CR background





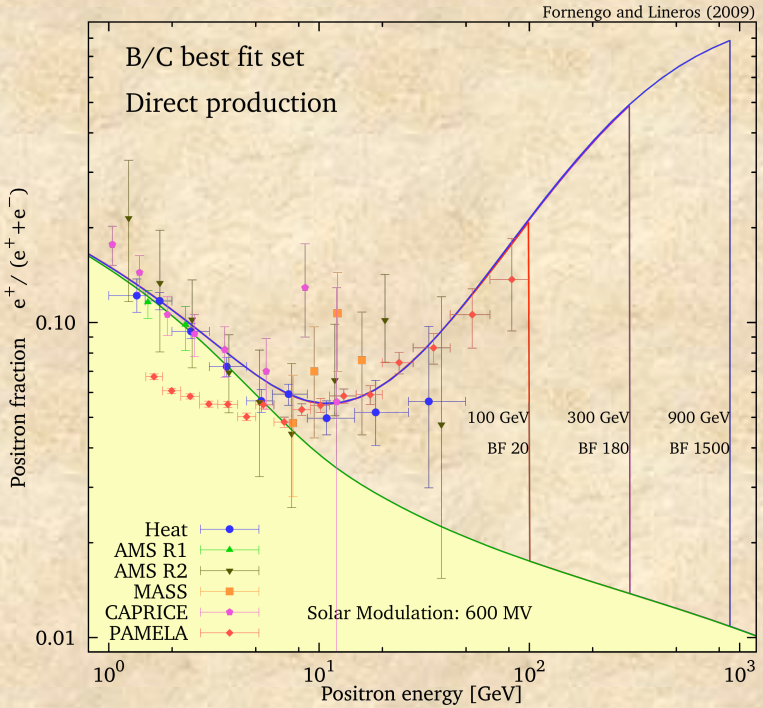
T. Delahaye, R. Lineros, F. Donato, N. Fornengo, J. Lavalle, P. Salati, R. Taillet (arXiv:0809.5268 [astro-ph])

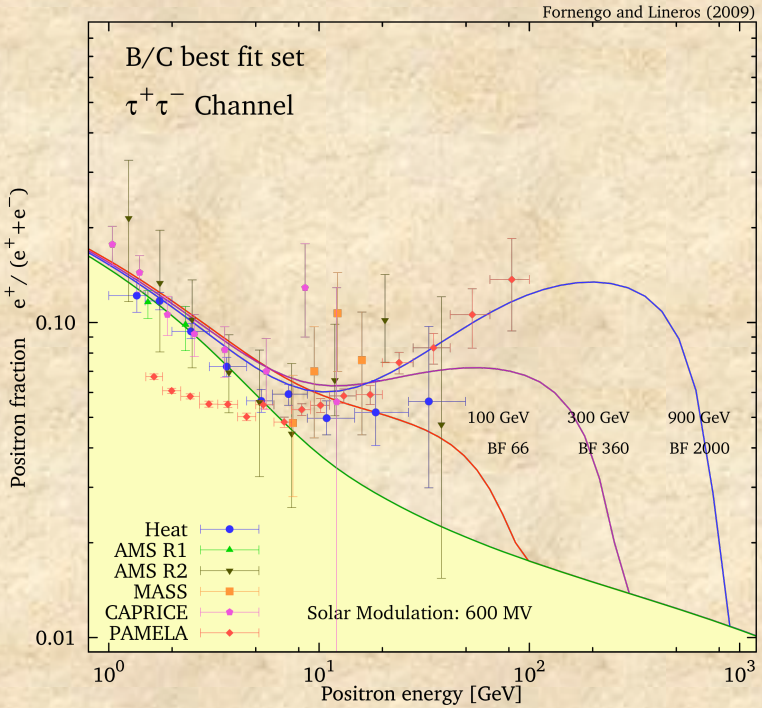
Positron fraction: astrophysical sources



S. Profumo, arXiv:0812.4457 [astro-ph]

Positron fraction: DM signal

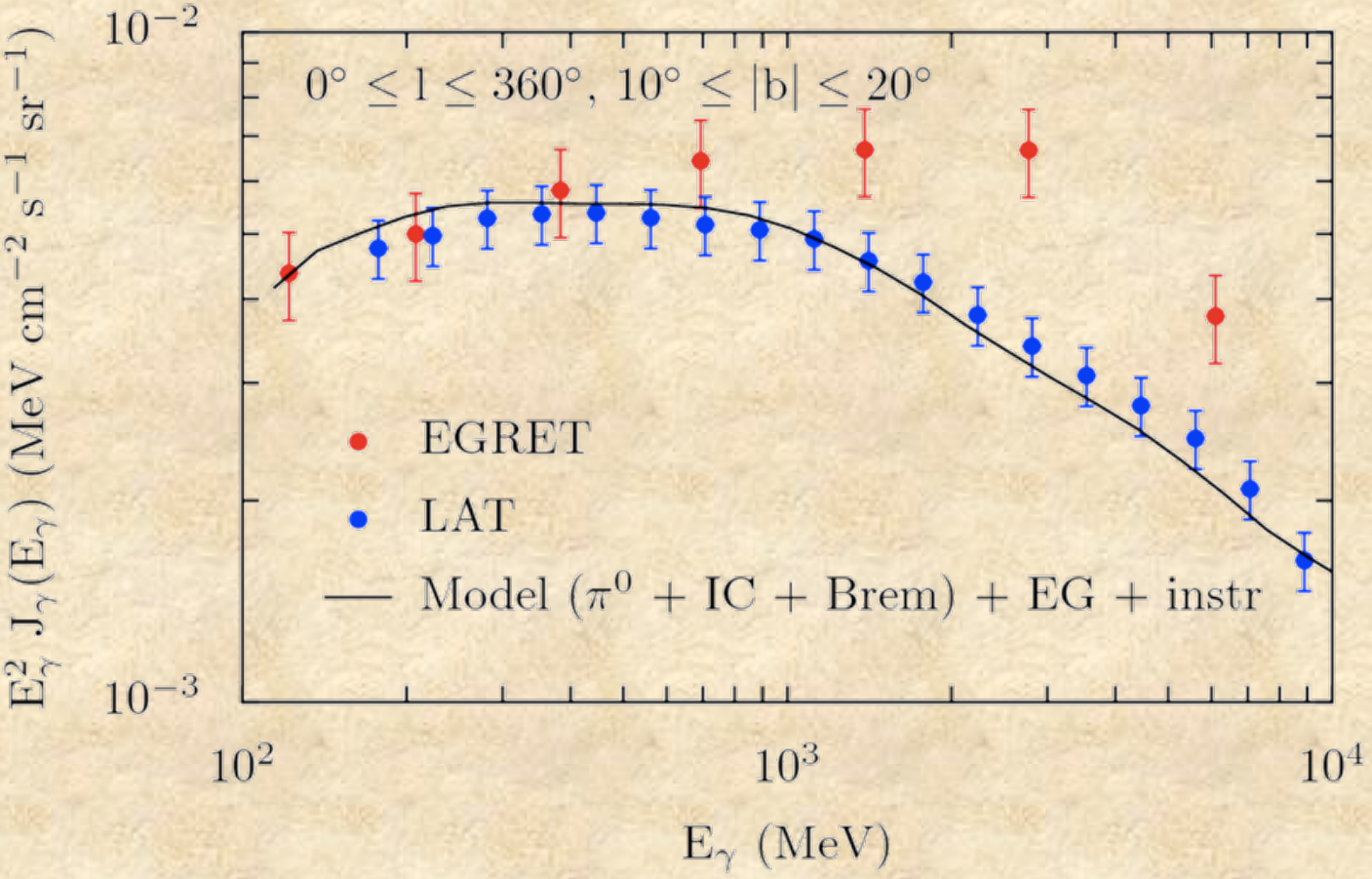




Hints of a signal?

- Direct detection: DAMA annual modulation of the rate
- Leptons: PAMELA positron fraction [ATIC ?]
- Gamma rays: EGRET "excess"

EGRET "excess"



Not confirmed by FERMI/LAT (Preliminary results)

C. Sgro', "Dark Matter Conference", GGI Institute, February 2009

Hints of a signal?

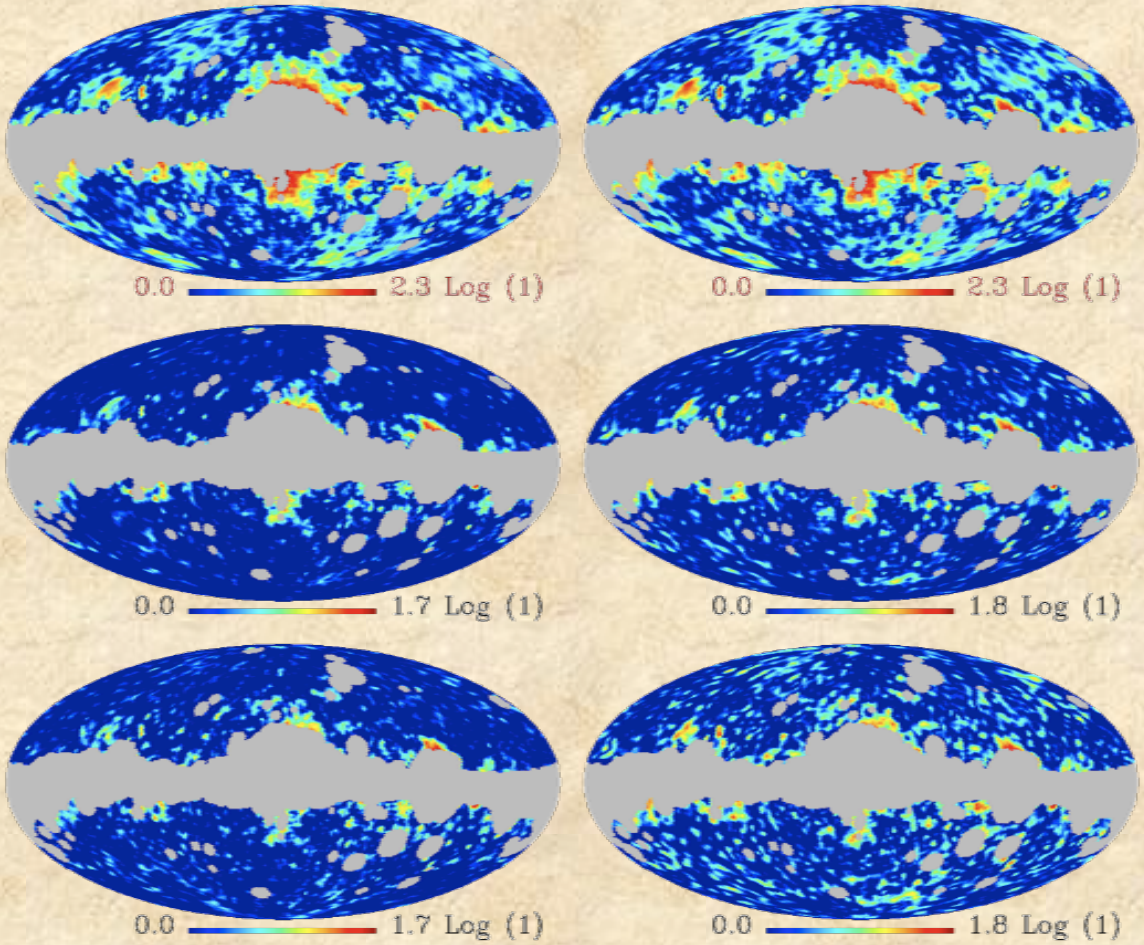
- Direct detection: DAMA annual modulation of the rate
- Leptons: PAMELA positron fraction [ATIC ?]
- Gamma rays: EGRET "excess" (not confirmed by FERMI)
- Microwaves: WMAP haze ?

WMAP haze

K band

Ka band

Q band



Statistical significance of the excess

DM interpretation: requires large boosts

D. Cumberbatch, J. Zunt, J. Silk, H. Eriksen, arXiv:0902.0039 [astro-ph]

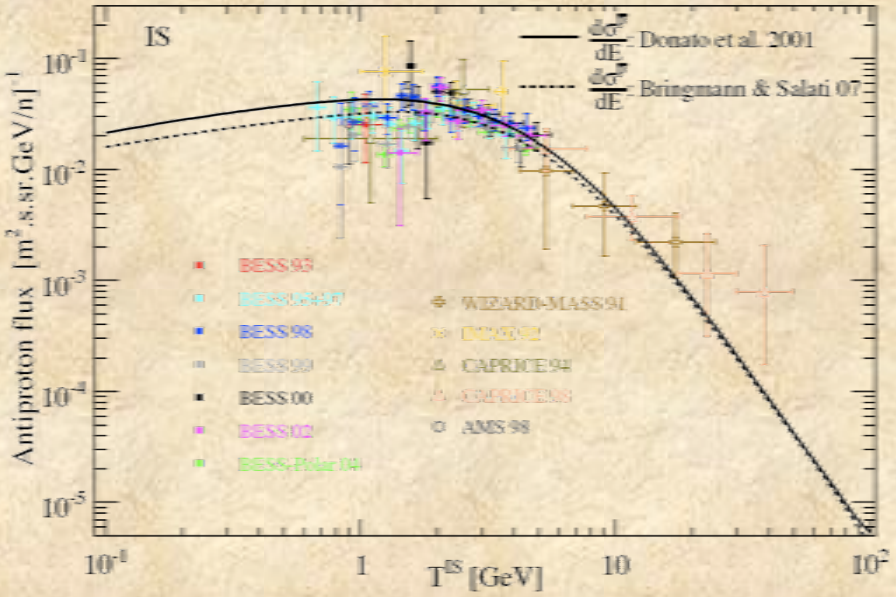
Hints of a signal?

- Direct detection: DAMA annual modulation of the rate
- Leptons: PAMELA positron fraction [ATIC e^-+e^+ flux ?]
- Gamma rays: EGRET "excess" (not confirmed by FERMI)
- Microwaves: WMAP haze ? (requires large boost factors)

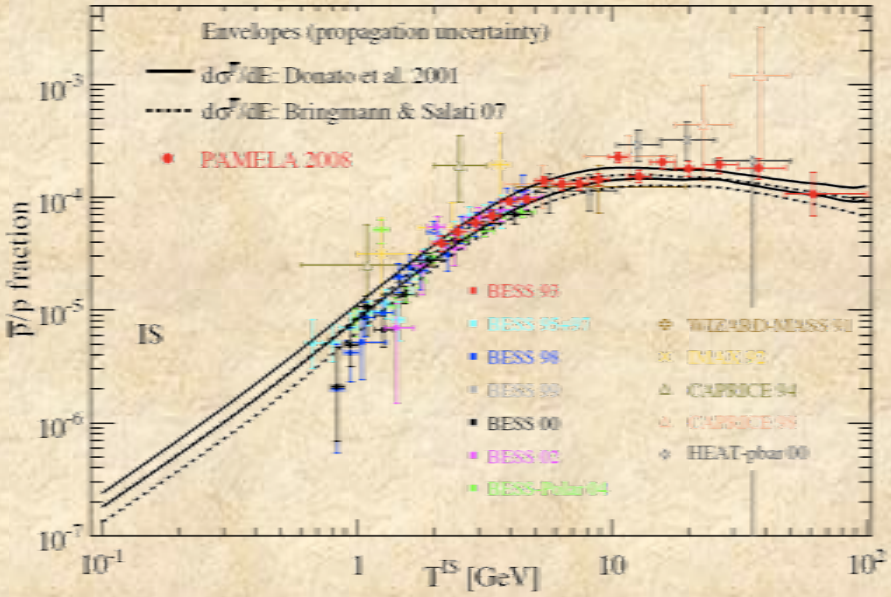
(...)

- Antiprotons, neutrino fluxes: no anomalies
- Antideuterons: for the near future

Secondary antiprotons



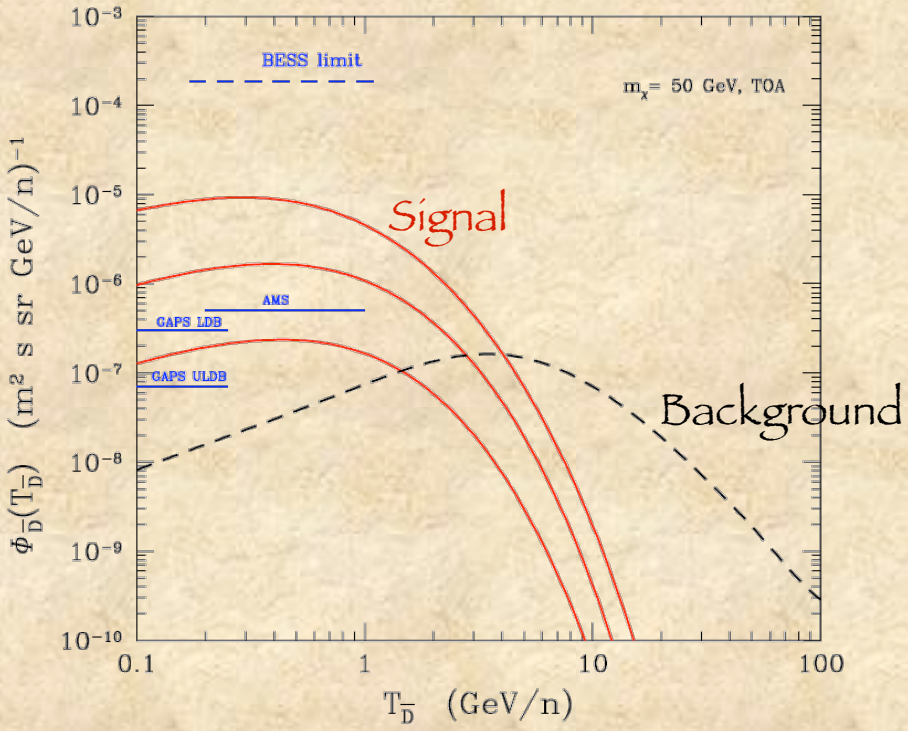
Antiproton flux

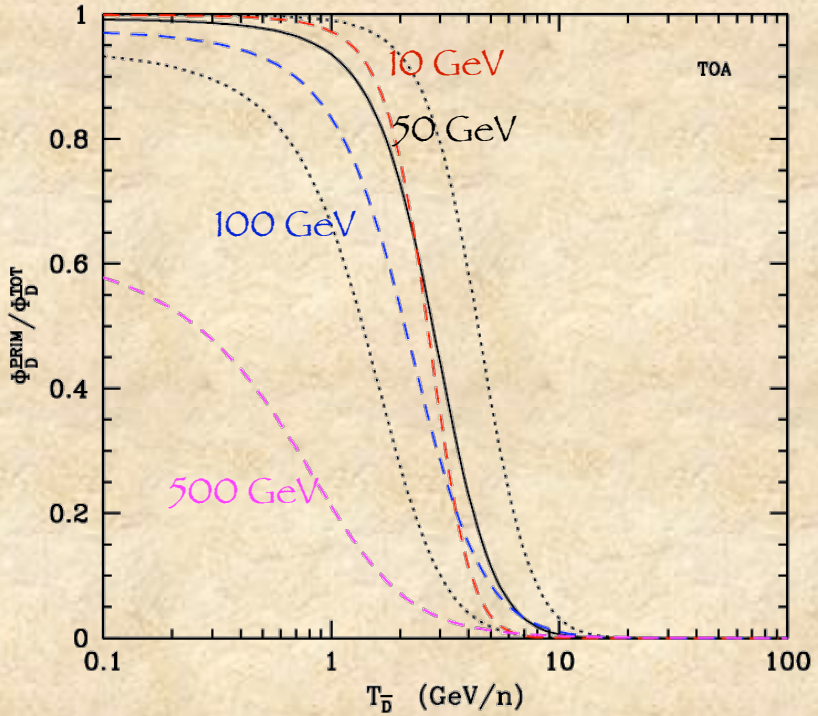


Antiproton/proton fraction

F. Donato, D. Maurin, P. Brun, T. Delahaye, P. Salati, arXiv.0810.5292 [astro-ph]

Cosmic Antideuterons





Signal with uncertainty band for:

- 50 GeV WIMP mass
- WMAP relic abundance

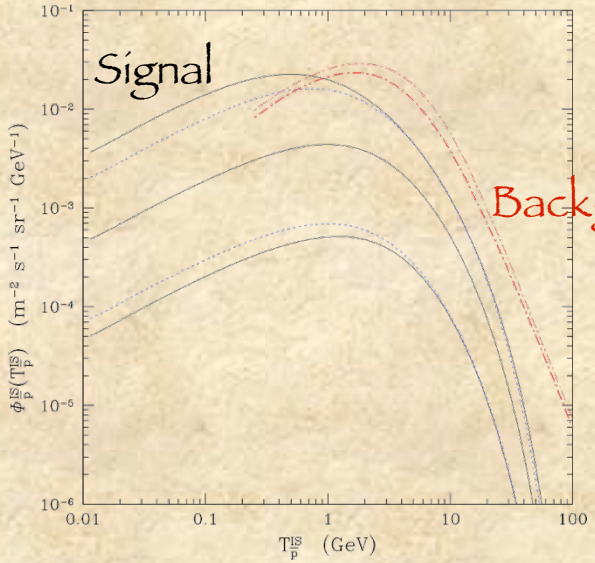
Signal/(Back+Signal) ratio

F. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

Particle DM (WIMPs)

- Astropysical searches may be used to set constraints on the properties of particle DM
- If a signal is detected, it may guide us toward the properties of the DM candidate
  - e.g.: PAMELA (positron fractions combined with antiproton fraction) prefers DM which preferably couples to leptons. This is compatible also with the DAMA annual modulation effect
- The large number of current and foreseen data will allow a deep study of the particle DM hypothesis
- This requires good knowledge of the sources of backgrounds and of the astrophysical uncertainties (still large)

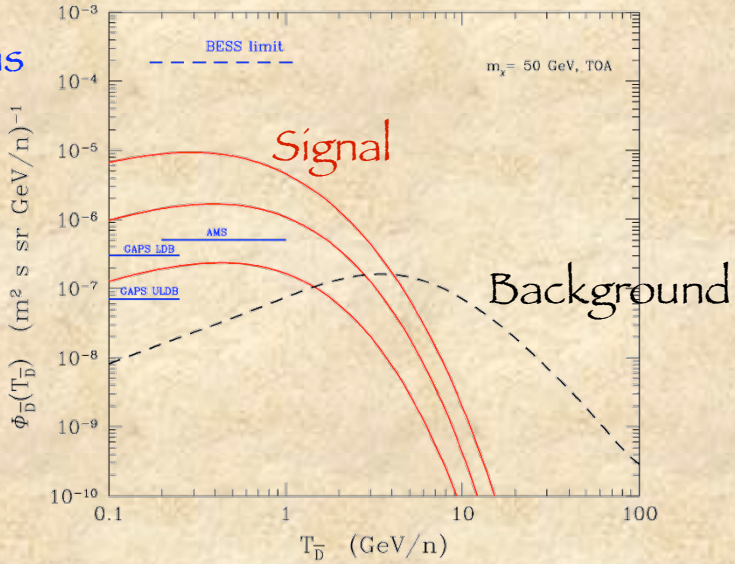
Astrophysical uncertainties on DM signals



Antiprotons

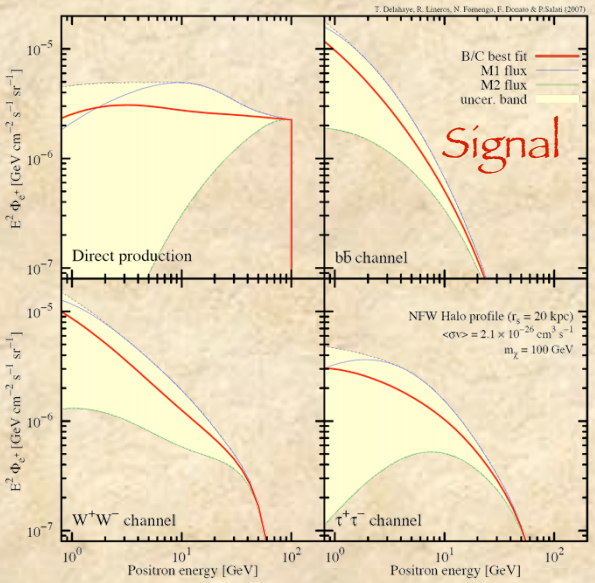
Antideuterons

m_X = 50 GeV



Positrons

m_X = 100 GeV



F. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

F. Donato, N.Fornengo, D. Maurin, P. Salati, R. Taillet, PRD 69 (2003) 063501

T. Delahaye, R. Lineros, F. Donato, N. Fornengo, P. Salati, Phys. Rev. D 77 (2008) 063527

Particle DM

- Particle DM: can be searched at accelerators
  - Tevatron, LHC, B Factories, ILC
- This requires to specify the nature of the DM candidate and the underlying model of New Physics
  - Supersymmetry
  - GUT models
  - Additional symmetries
  - Extra-dimensions
  - Models of string theory or branes
  - (...)

Non-baryonic DM candidates

- Non supersymmetric candidates
  - Neutrino
  - "Minimal" candidates
  - Axion
  - Kaluza-Klein fields
  - Little Higgs models
  - Mirror baryons

  (…)
- Supersymmetric candidates
  - Neutralino
  - Sneutrino
  - Gravitino
  - Axino
  - Messenger fields
  - Stable non-topological solitons (Q-balls)
  - Heavy non-thermal relics

  (…)

- Low energy MSSM
  - Universal mass params
  - Light neutralinos
- Minimal SUGRA
- Non-minimal SUGRA
  - Higgs sector
  - Sfermion sector
  - Gaugino sector
- NMSSM
- Anomaly mediated ~~SUSY~~
- (…)

What astrophysical signals probe?

- Direct detection:
  - (In)elastic scattering cross section on nuclei (non-relativistic)
  - Scattering cross section on electrons
- Indirect detection of antimatter, gamma rays, multi-λ photons
  - Annihilation cross section (non-relativistic)
- Indirect detection at neutrino telescopes:
  - Elastic scattering cross section on nuclei (or electrons)
  - BR of annihilation cross section

What accelerators probe?

- DM candidate
  - Contributes to missing momenta (since neutral and massive)
- New Physics (NP) spectrum
  - Masses and couplings (partly)
- The mechanism of production at accelerators relies on processes different from the those producing the astrophysical signals
- Accelerator physics and astrophysical signals may either probe the same or different sectors of the NP parameter space
- Comparisons have to be performed in specific models of NP

Minimal Supergravity (mSUGRA)

$\alpha_i(M_{\rm GUT}) \equiv \alpha_0 \qquad i = 1,2,3$

$M_{\rm GUT} = 2 \cdot 10^{16}$ GeV

$$
\begin{aligned}
m_i^2(M_{\rm GUT}) &\equiv m_0^2 \\
M_j(M_{\rm GUT}) &\equiv M_{1/2} \\
A_k(M_{\rm GUT}) &\equiv A_0 m_0^2
\end{aligned}
$$

$$
\begin{aligned}
i &= L, E, Q, U, D, H_1, H_2 \\
j &= 1,2,3 \\
k &= U, D, E \quad 3^{\rm rd}\,\text{family}
\end{aligned}
$$

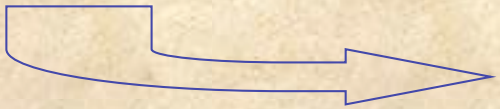
$$
\begin{aligned}
M_1, M_2, M_3 &\longleftarrow M_{1/2} \\
m_{H_1}^2, m_{H_2}^2, m_L^2, m_E^2, m_Q^2, m_U^2, m_D^2 &\longleftarrow m_0^2 \\
A_t, A_b, A_\tau &\longleftarrow A_0
\end{aligned}
$$

EW scale

GUT scale

- The parameters at the EW scale are obtained by RGE evolution from their universal values at the GUT scale

- In addition, EWSB is induced radiatively through the RGE evolution of the Higgs mass parameters



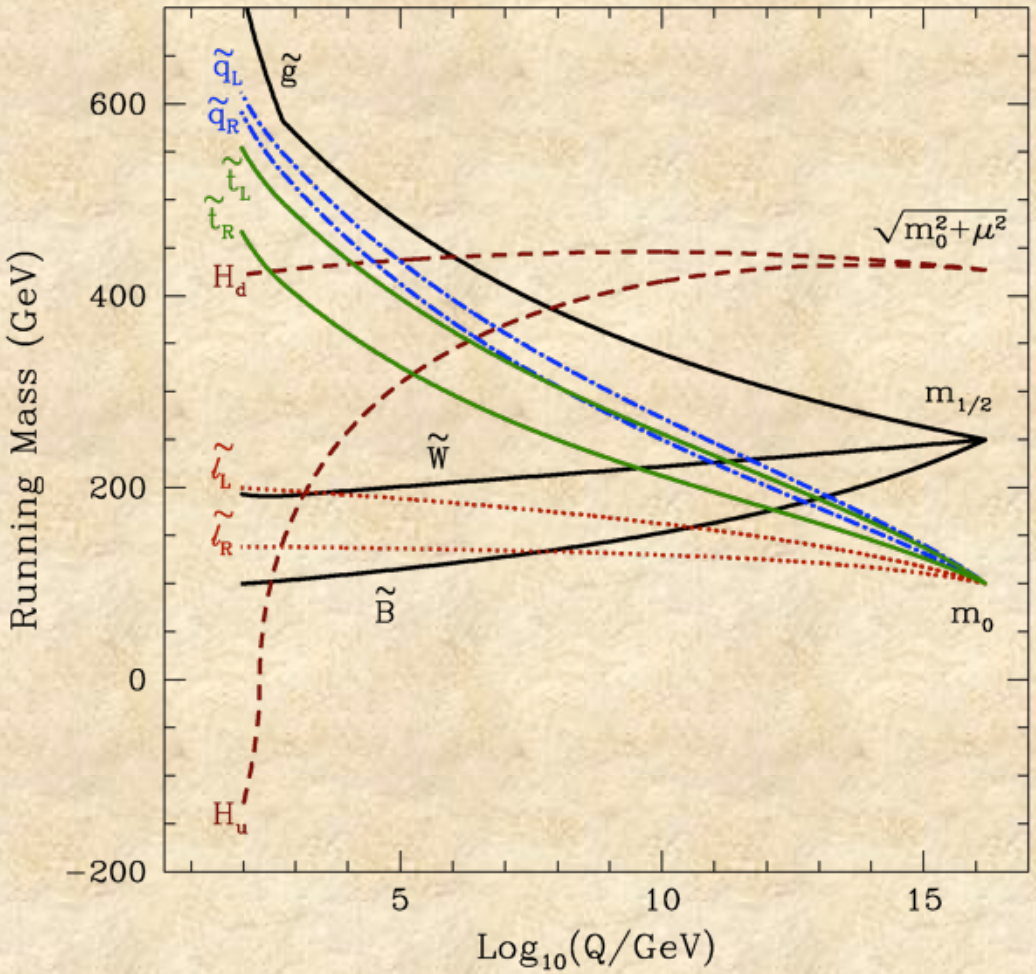
$$m_A \ , \ \mu^2$$

Free parameters: $M_{1/2} \ , \ m_0 \ , \ A_0 \ , \ \tan\beta \ , \ \mathrm{sign}(\mu)$

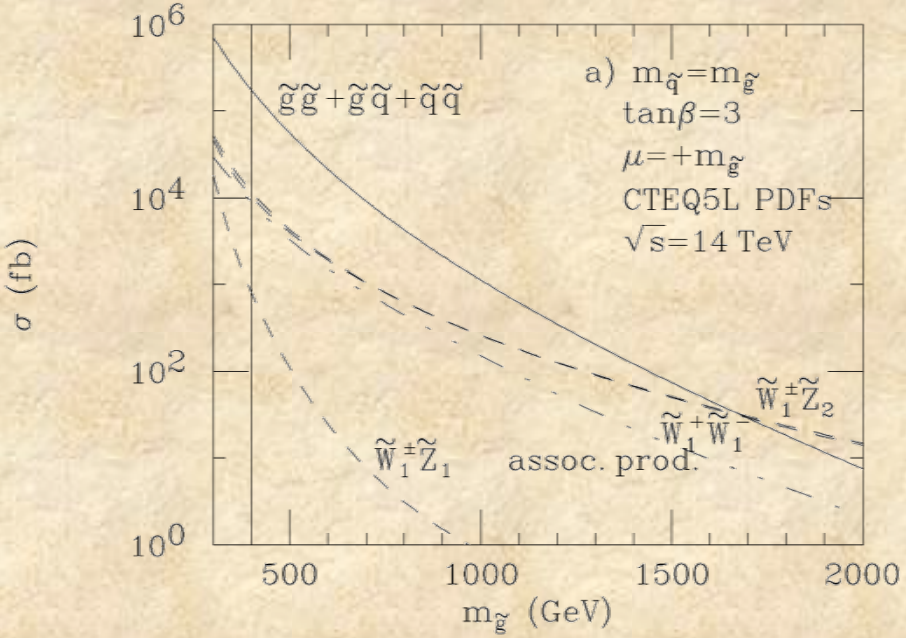
$$\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$$

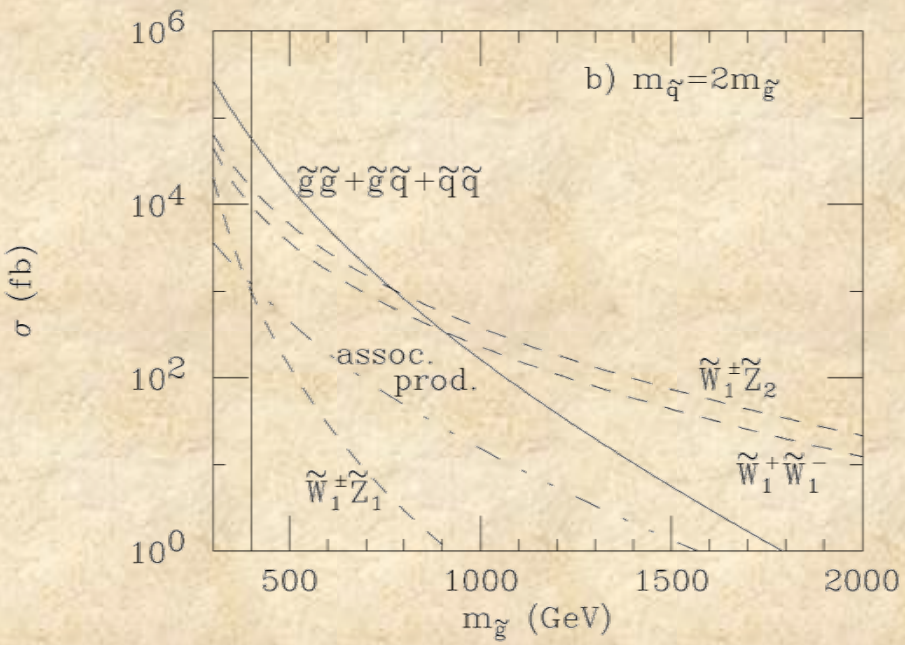
Neutralino LSP: almost pure bino

Mass parameters evolution



SUSY particle productions at LHC





H. Baer, 0901.4732 [hep-ph]

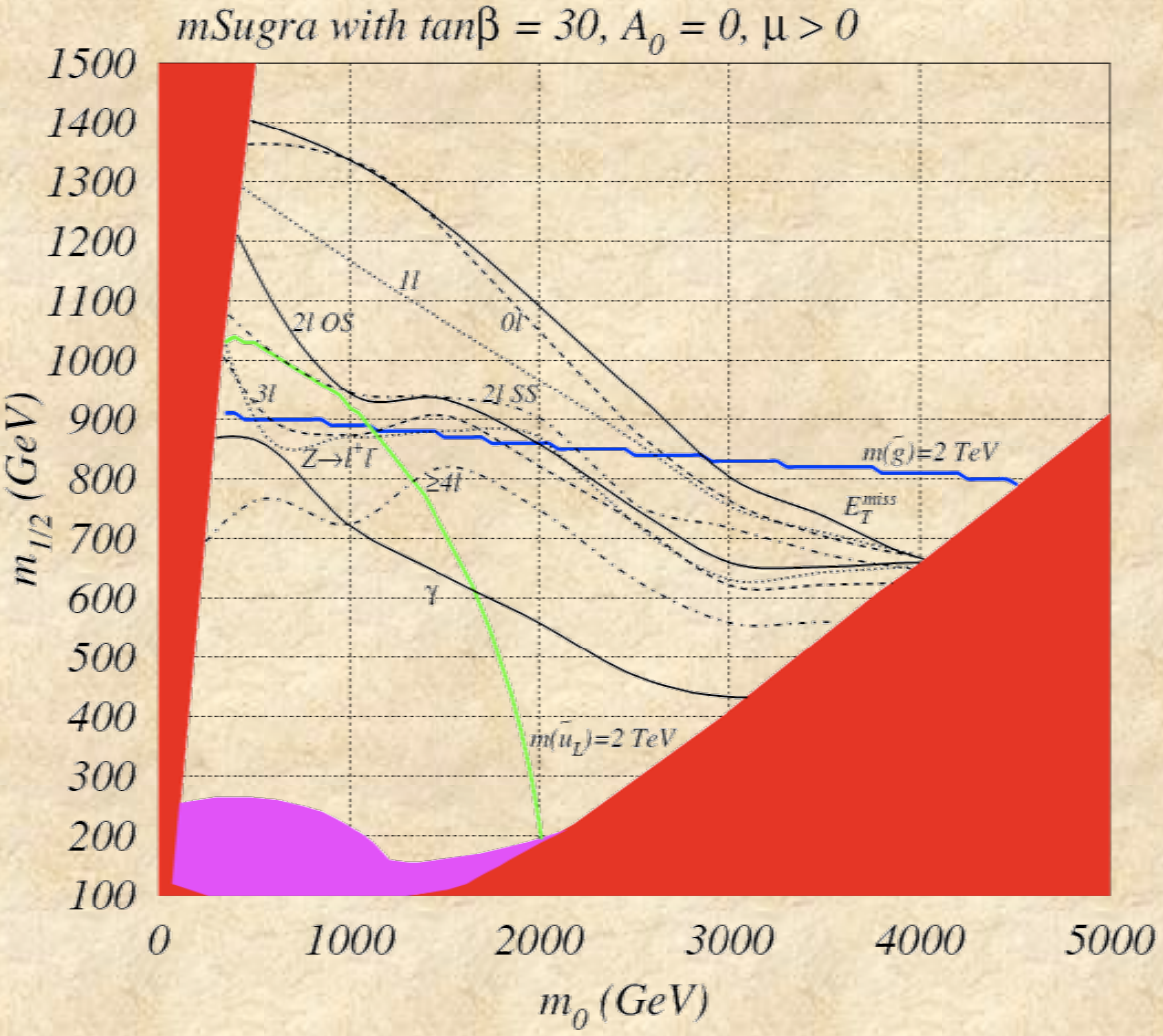
SUSY particle signatures at LHC

Typical SUSY events at LHC mainly result in gluino and squark production, followed by their cascade decays

- zero lepton $+jets+ \not{E}_T$ events,
- one lepton $+jets+ \not{E}_T$ events,
- two opposite sign leptons $+jets+ \not{E}_T$ events (OS),
  - same-flavor (OSSF),
  - different flavor (OSDF),
- two same sign leptons $+jets+ \not{E}_T$ events (SS),
- three leptons $+jets+ \not{E}_T$ events (3ℓ),
- four (or more) leptons $+jets+ \not{E}_T$ events (4ℓ).

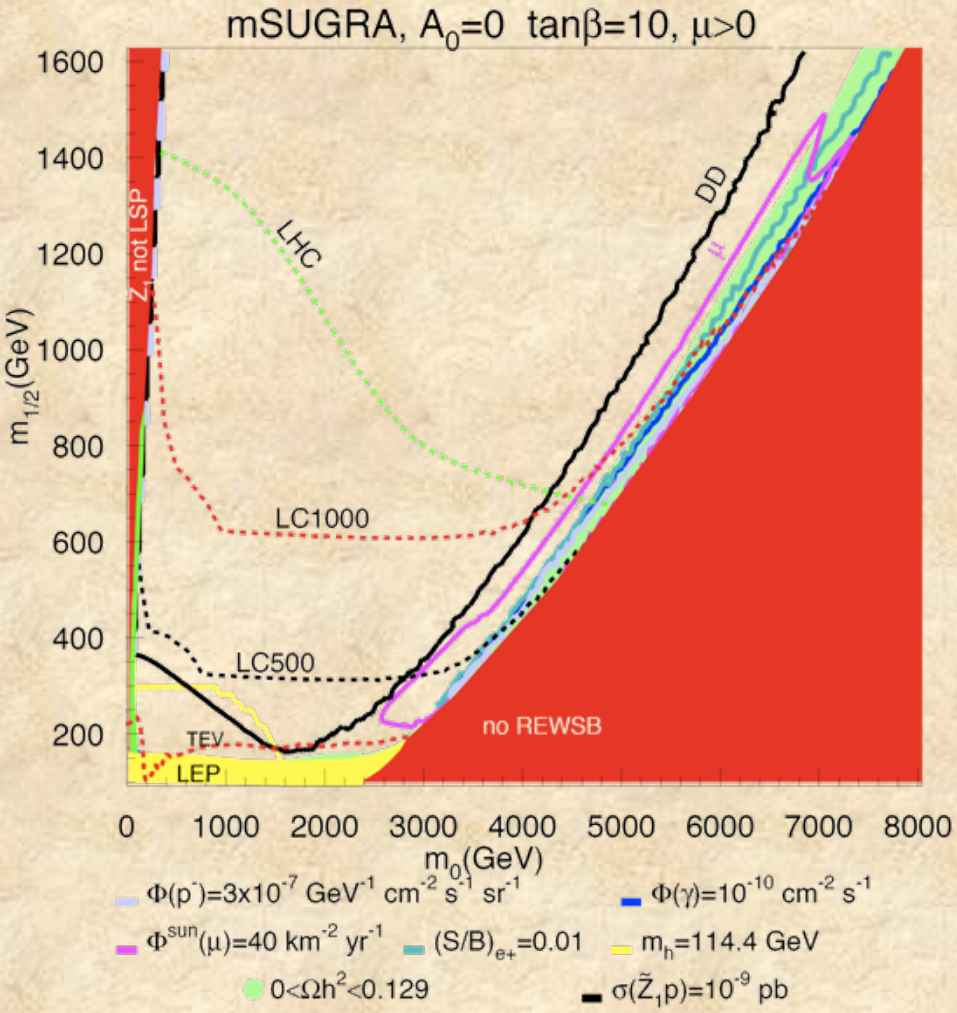
Reach of LHC in mSUGRA

100 fb^{-1}



H. Baer, 0901.4732 [hep-ph]

LHC reach and astrophysical DM searches



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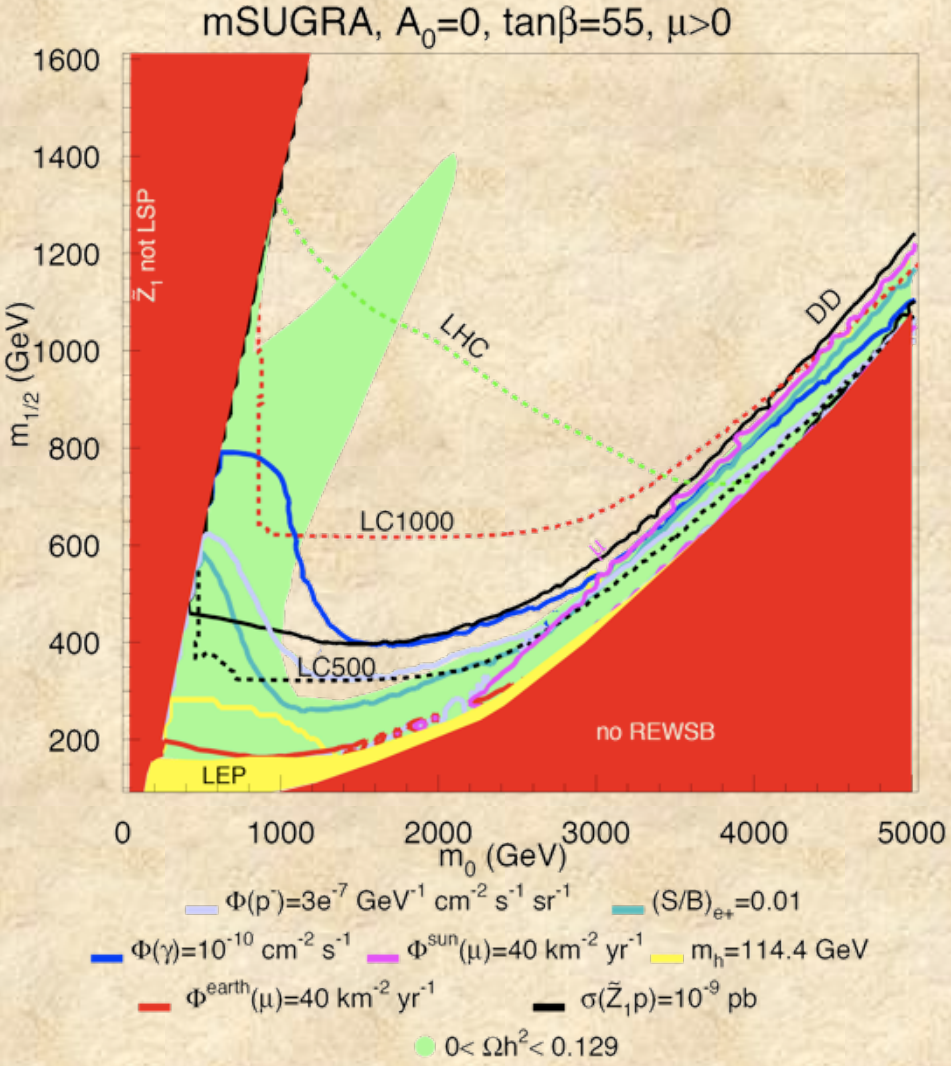
LHC reach and astrophysical DM searches



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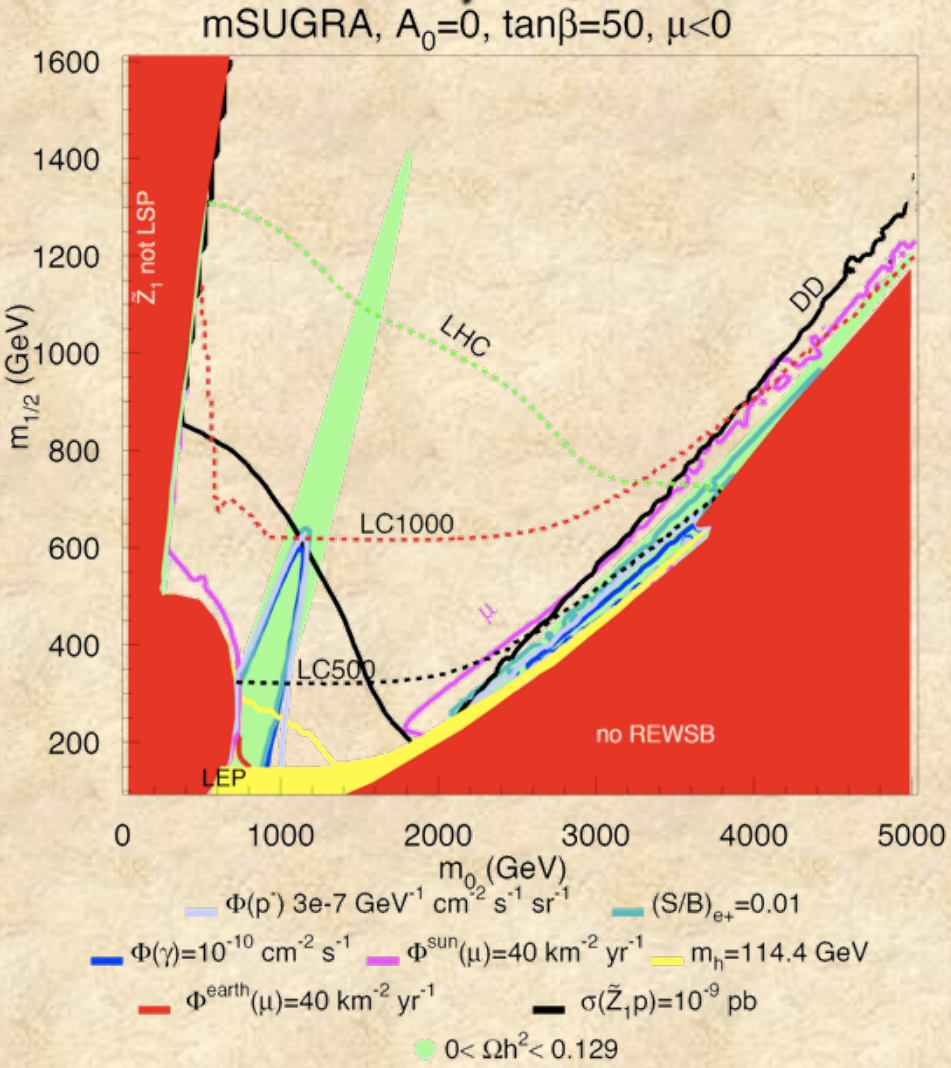
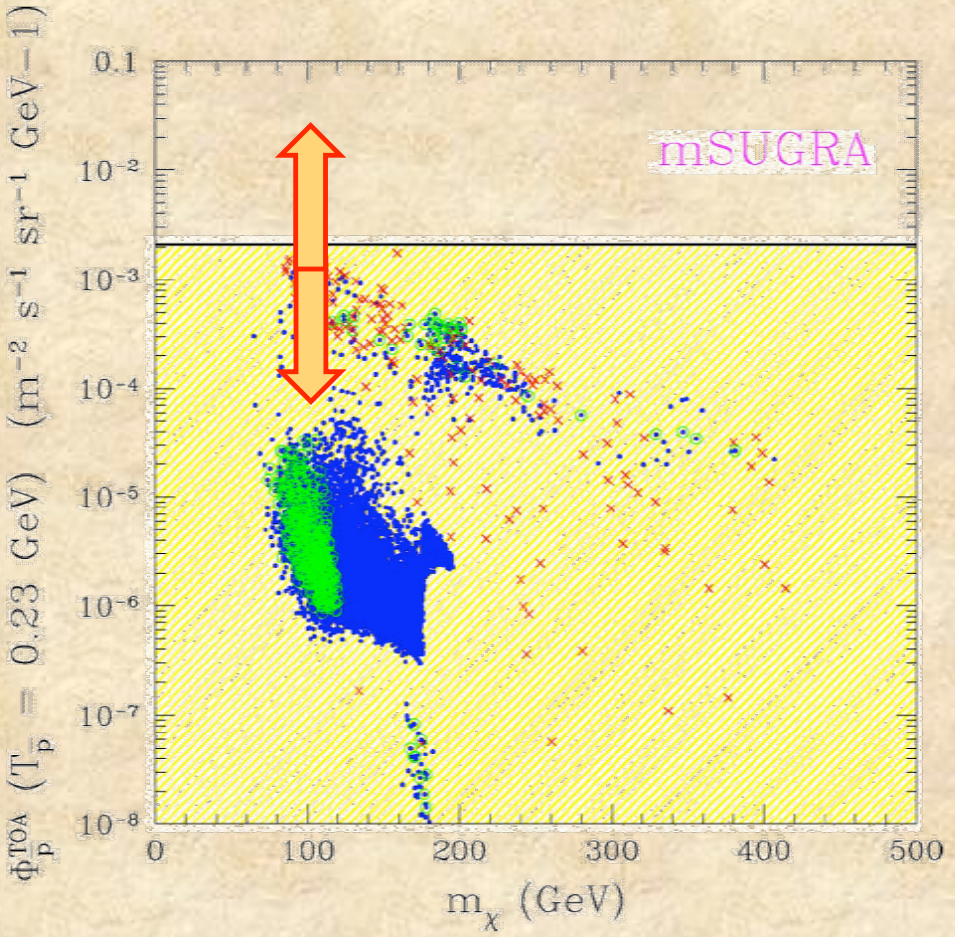


H. Baer, 0901.4732 [hep-ph]

Cosmic antiprotons

SUGRA

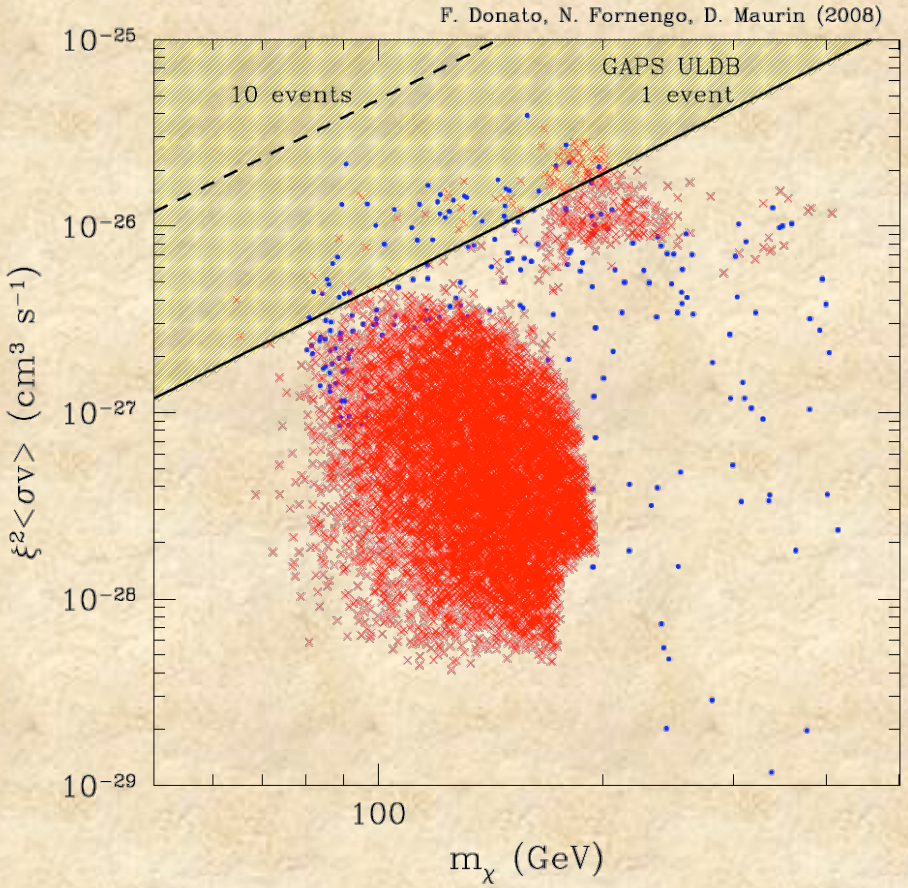


Best-fit astro params

F. Donato, N.Fornengo, D. Mauron, P. Salati, R. Taillet, PRD 69 (2004) 063501

Cosmic antideuterons

SUGRA



Best-fit astro params

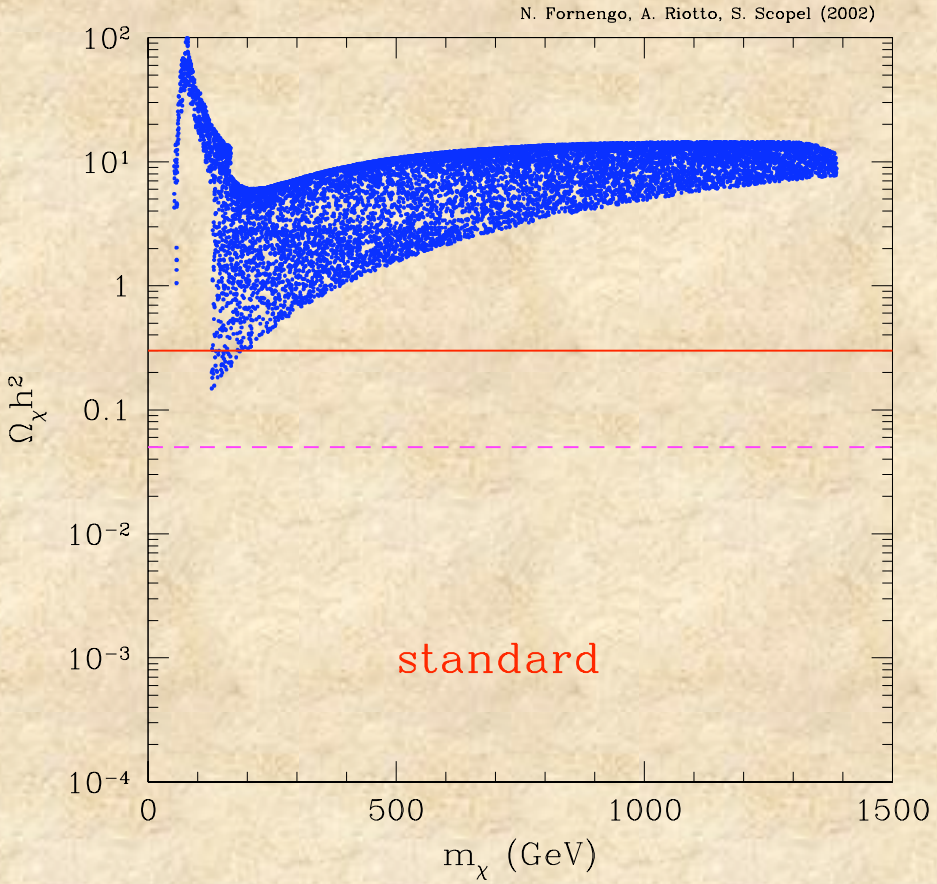
F. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

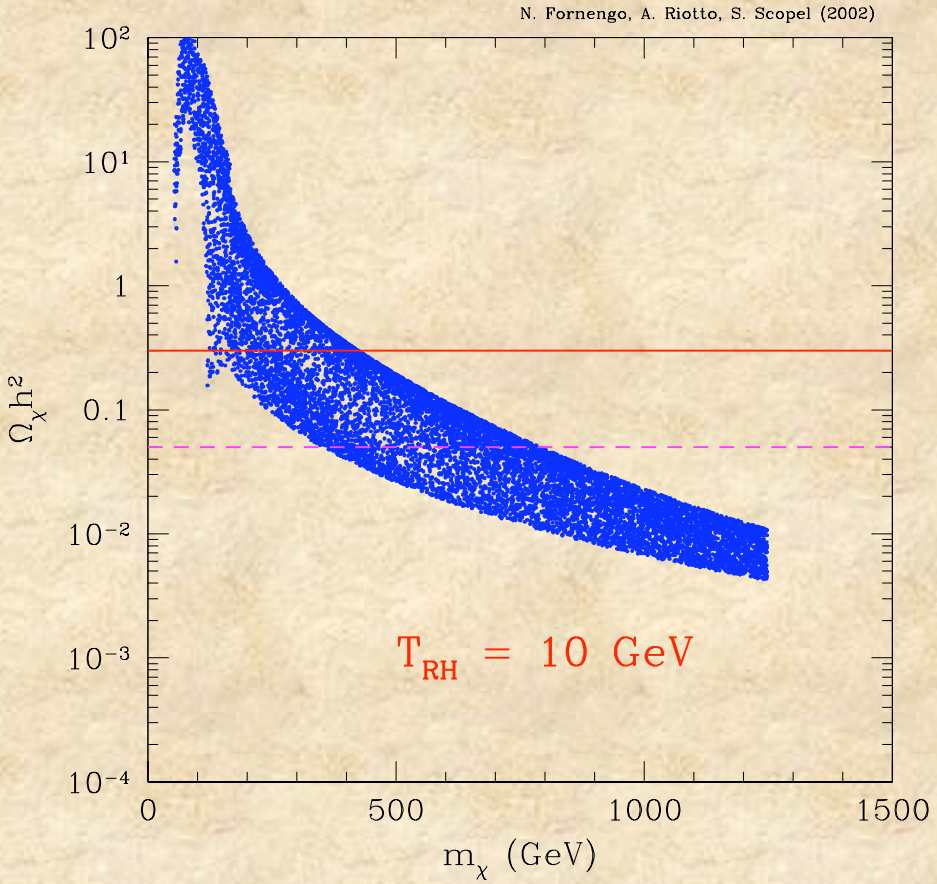
Cosmology may play a role!

- Cosmologically allowed regions depend on the mechanism of DM formation in the early Universe (pre-BBN era)

- The thermal history of the Universe before or around the time of decoupling may drastically change the current value of the relic abundance for a given candidate

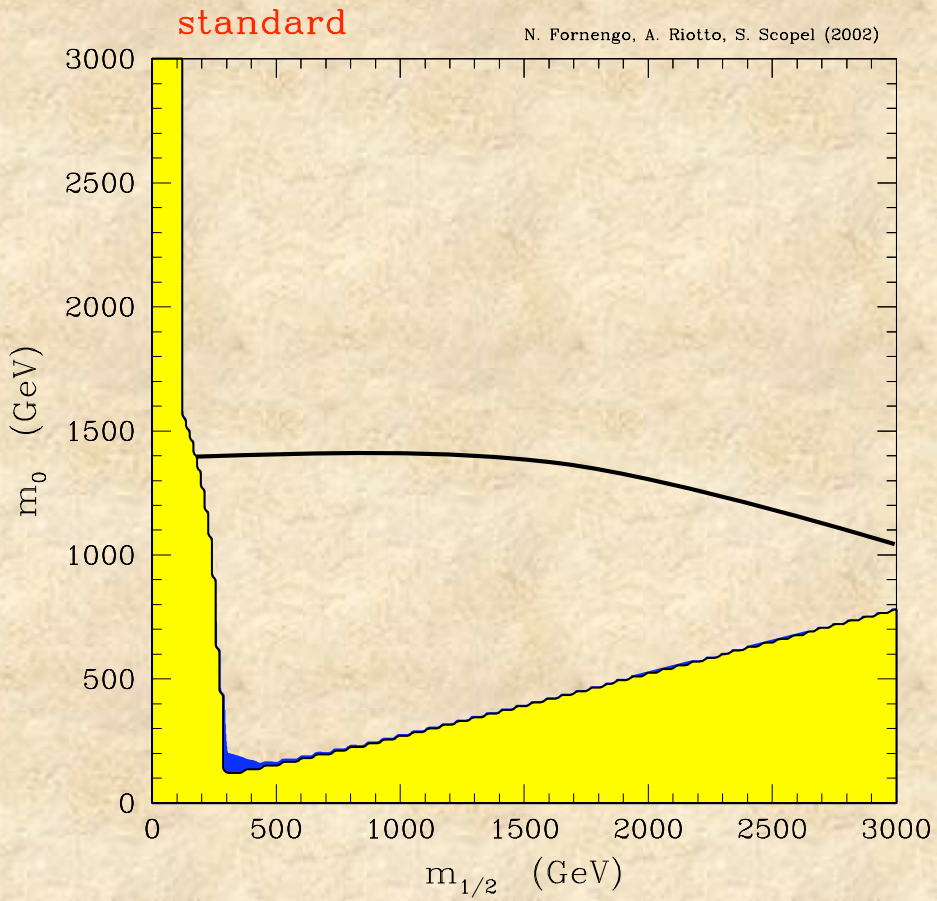
Low-reheating cosmology

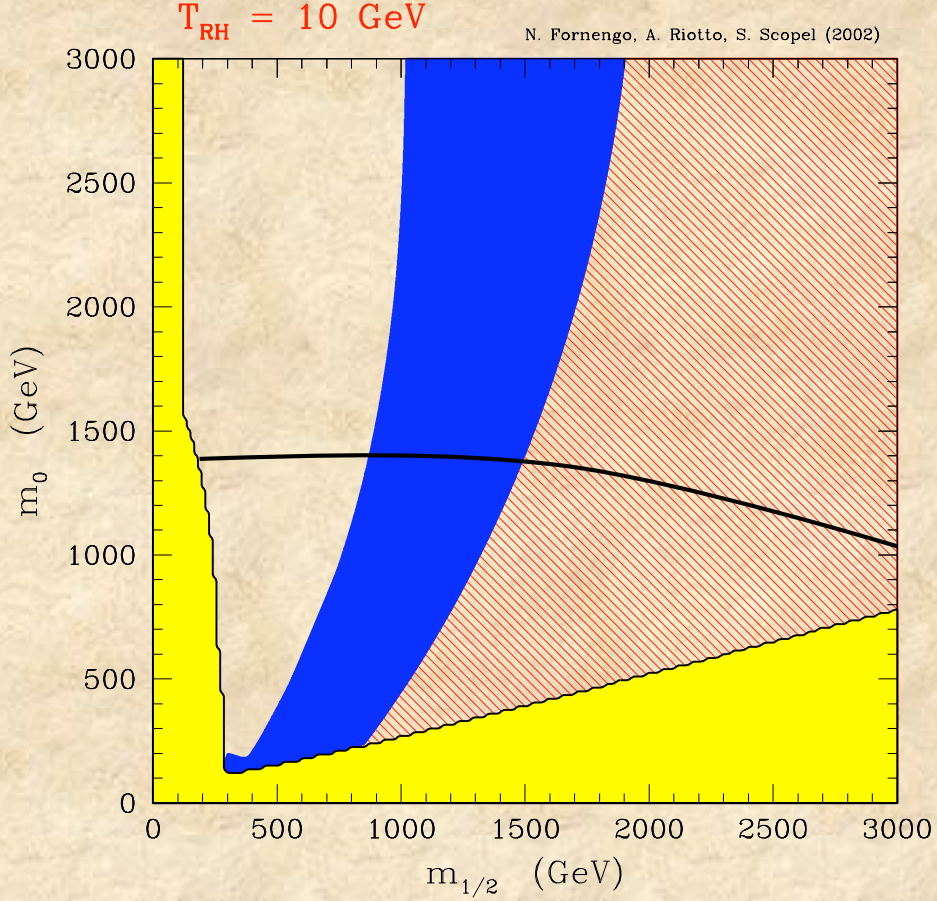




N. Fornengo, A. Riotto, S. Scopel, PRD 67(2003) 023514

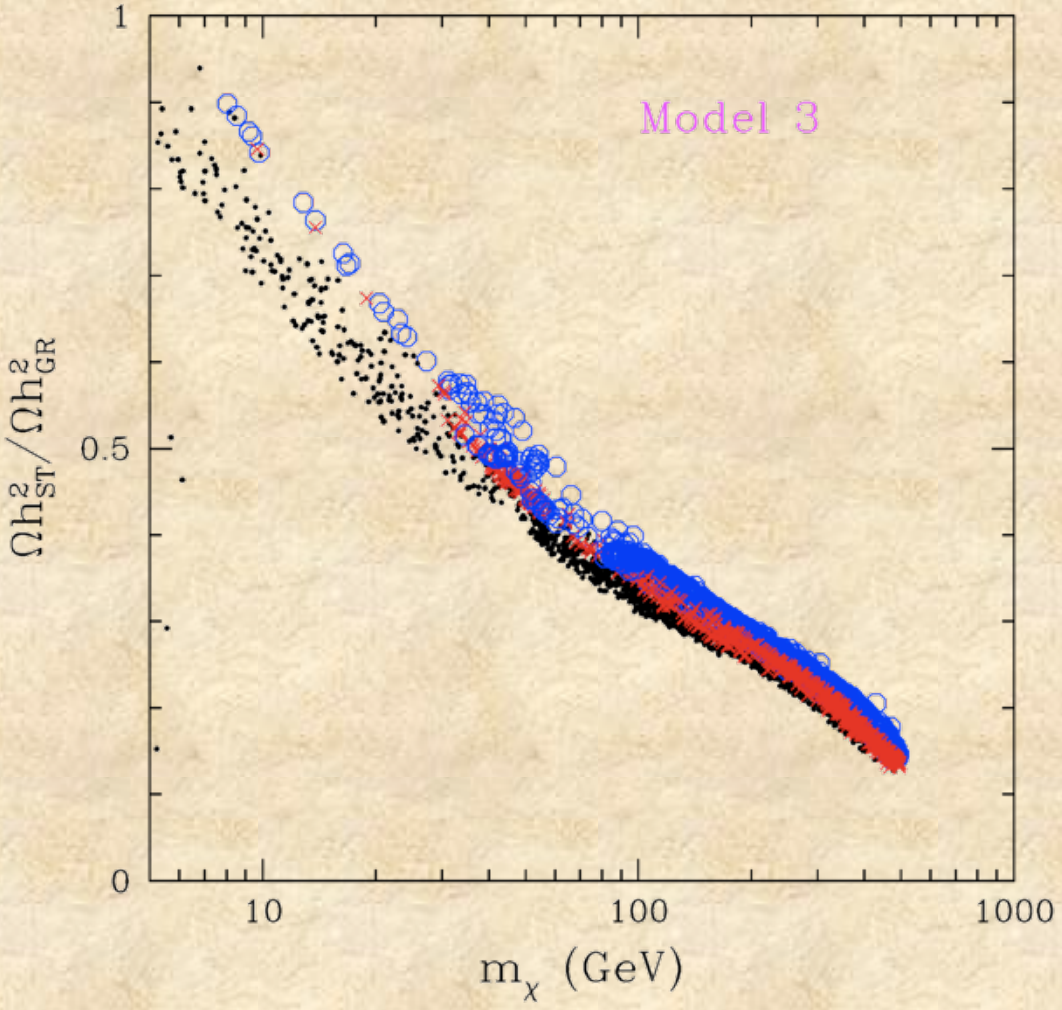
Low-reheating cosmology





N. Fornengo, A. Riotto, S. Scopel, PRD 67(2003) 023514

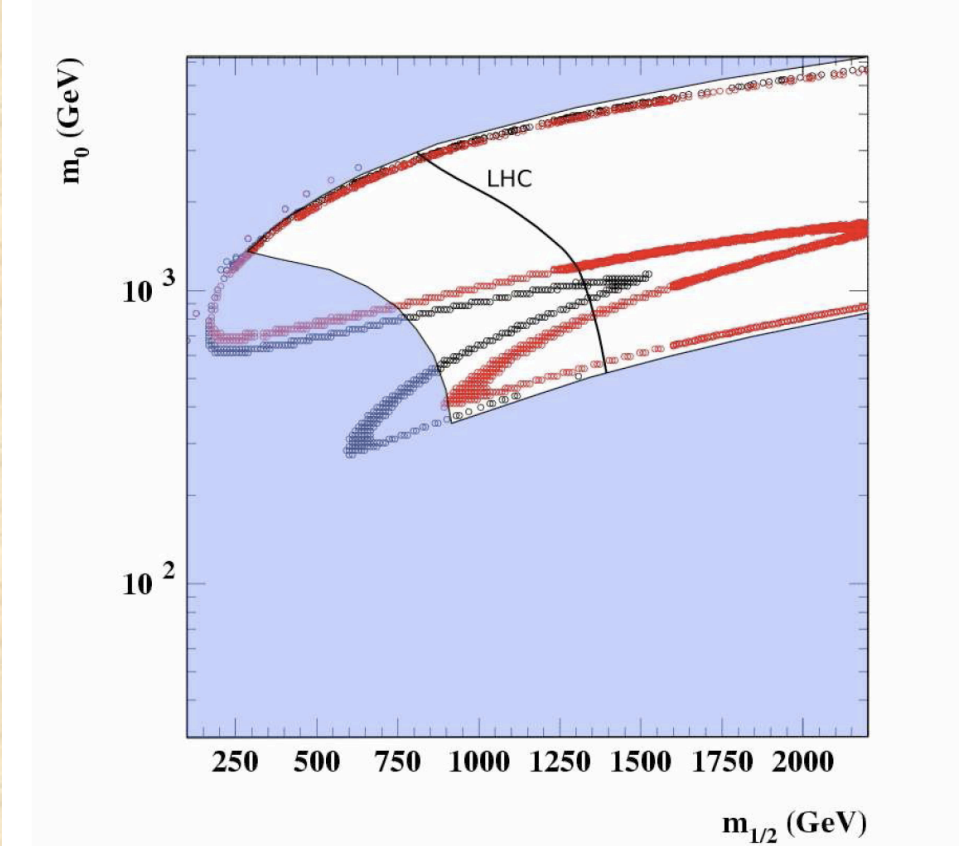
Scalar-tensor gravity with 2 scalar fields



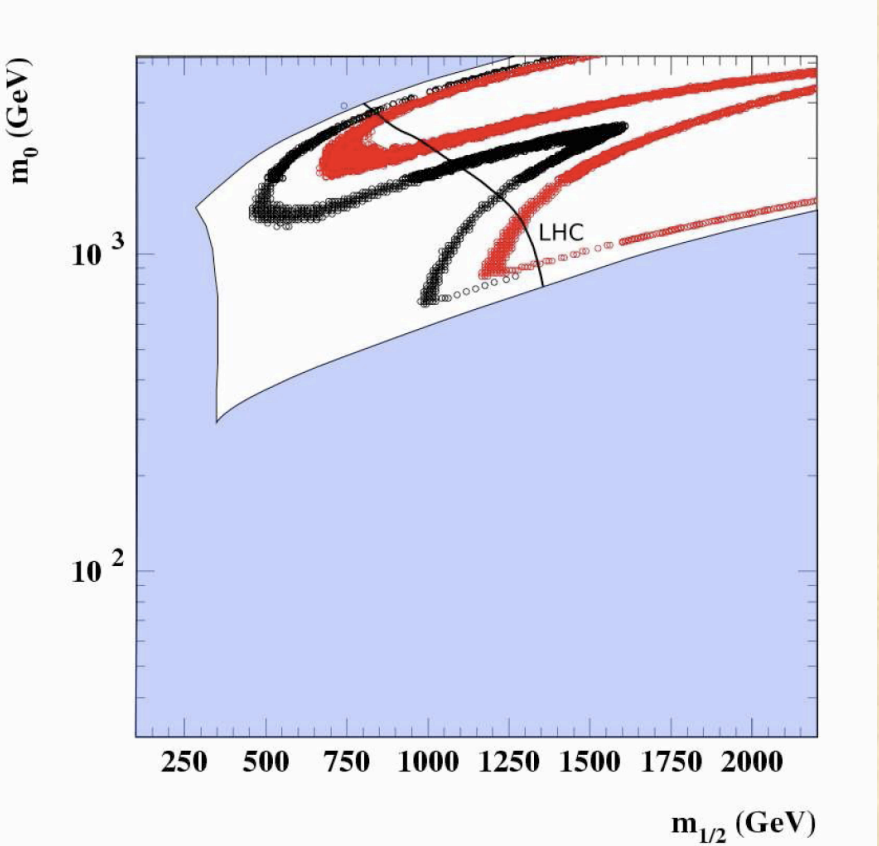
R. Catena, N. Fornengo, A. Masiero, M. Pietroni, M. Schelke, JHEP 0810 (2008) 003

Impact on mSUGRA

$\tan\beta = 45$



$\tan\beta = 53$



R. Catena, N. Fornengo, A. Masiero, M. Pietroni, M. Schelke, JHEP 0810 (2008) 003

Non-universal SUGRA

- Non-universality in the Higgs sector

$$\boxed{\begin{aligned} m_i^2(M_{\rm GUT}) &\equiv m_0^2 \\ m_{\rm H_a}^2(M_{\rm GUT}) &\equiv m_0^2(1+\delta_a) \end{aligned}} \qquad \begin{aligned} i &= L, E, Q, U, D \\ a &= 1, 2 \end{aligned}$$

EWSB is affected

Neutralino LSP: mixed neutralinos can arise

- Non-universality in the sfermion sector

$$\boxed{m_i^2(M_{\rm GUT}) \equiv m_0^2(1+\delta_i)} \qquad i = L, E, Q, U, D$$

- Non-universality in the gaugino sector

$$\boxed{M_j(M_{\rm GUT}) \equiv M_{1/2}(1+\delta_j)} \qquad j = 1, 2, 3$$

Low-energy effective MSSM

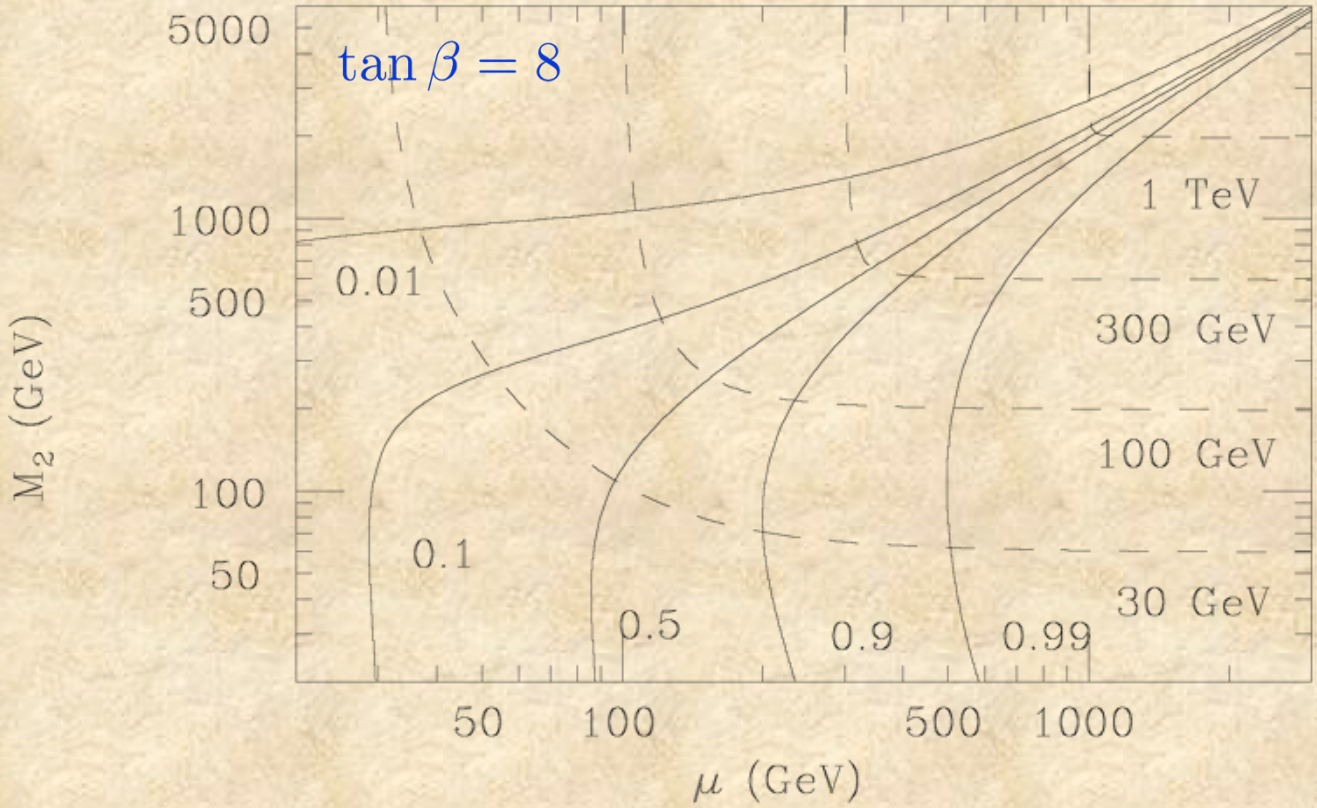
$$
\begin{aligned}
M_1(M_{\rm EW}) &\equiv \frac{5}{3}\tan^2\theta_W\ M_2(M_{\rm EW})\ ^{(*)} \\
m_L^2(M_{\rm EW}) = m_E^2(M_{\rm EW}) &\equiv m_{\tilde{l}}^2 \\
m_Q^2(M_{\rm EW}) = m_U^2(M_{\rm EW}) = m_D^2(M_{\rm EW}) &\equiv m_{\tilde{q}}^2 \\
A_t(M_{\rm EW}) = A_b(M_{\rm EW}) &\equiv A m_{\tilde{q}} \\
A_\tau(M_{\rm EW}) &\equiv A m_{\tilde{l}} \\
&\tan\beta \\
&m_A \\
&\mu
\end{aligned}
$$

Free parameters: $M_2\ ,\ m_{\tilde{l}}\ ,\ m_{\tilde{q}}\ ,\ A\ ,\ \tan\beta\ ,\ m_A\ ,\ \mu$

$^{(*)}$From GUT assumption: $M_1(M_{\rm GUT}) = M_2(M_{\rm GUT}) = M_3(M_{\rm GUT}) \equiv M_{1/2}$

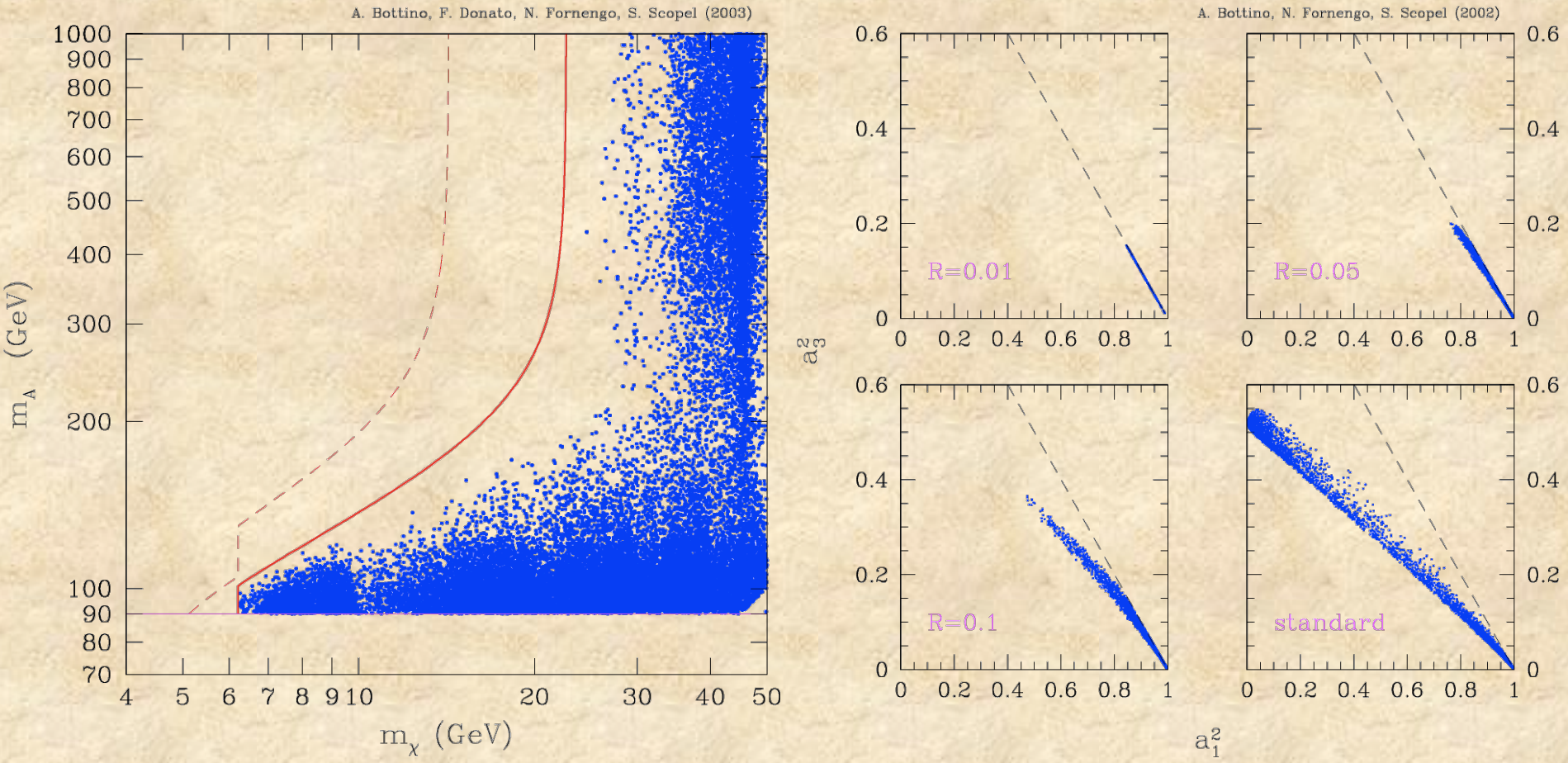
MSSM

Neutralino LSP: either bino, mixed or higgsino



MSSM + Gaugino non-universality

$$M_1(M_{\rm EW}) \equiv R\, M_2(M_{\rm EW})$$

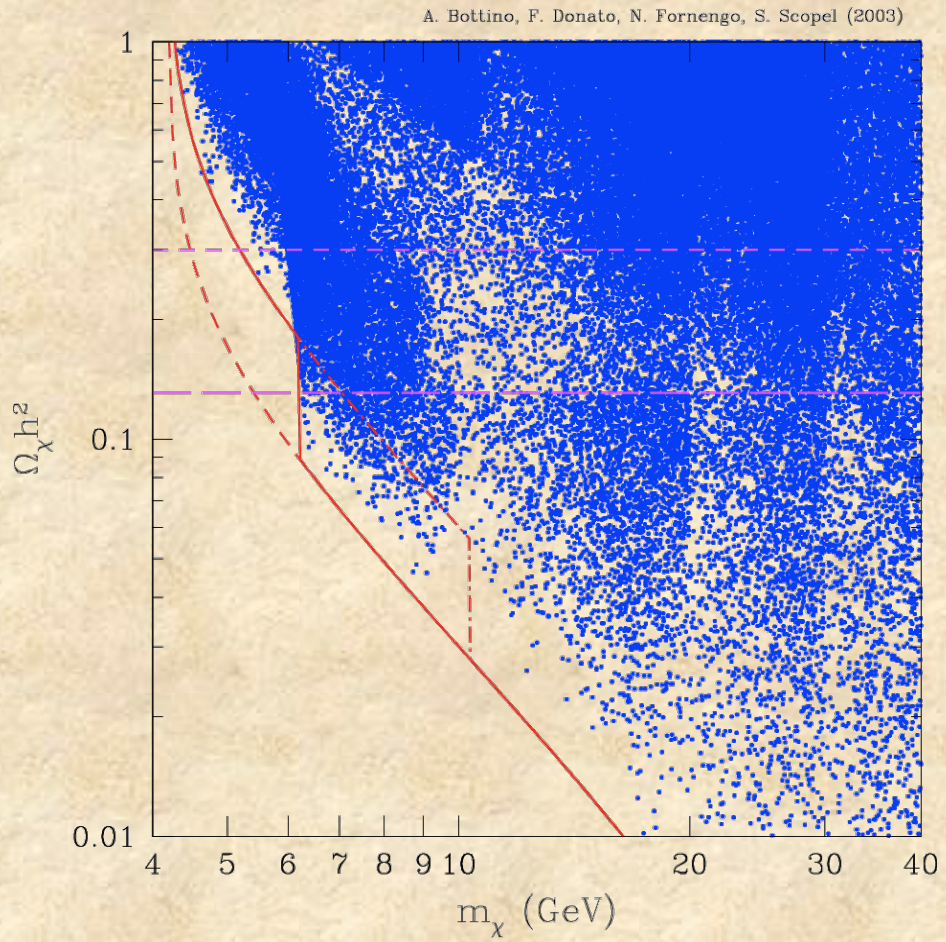


Light Neutralino LSP: almost pure bino + fraction of higgsino

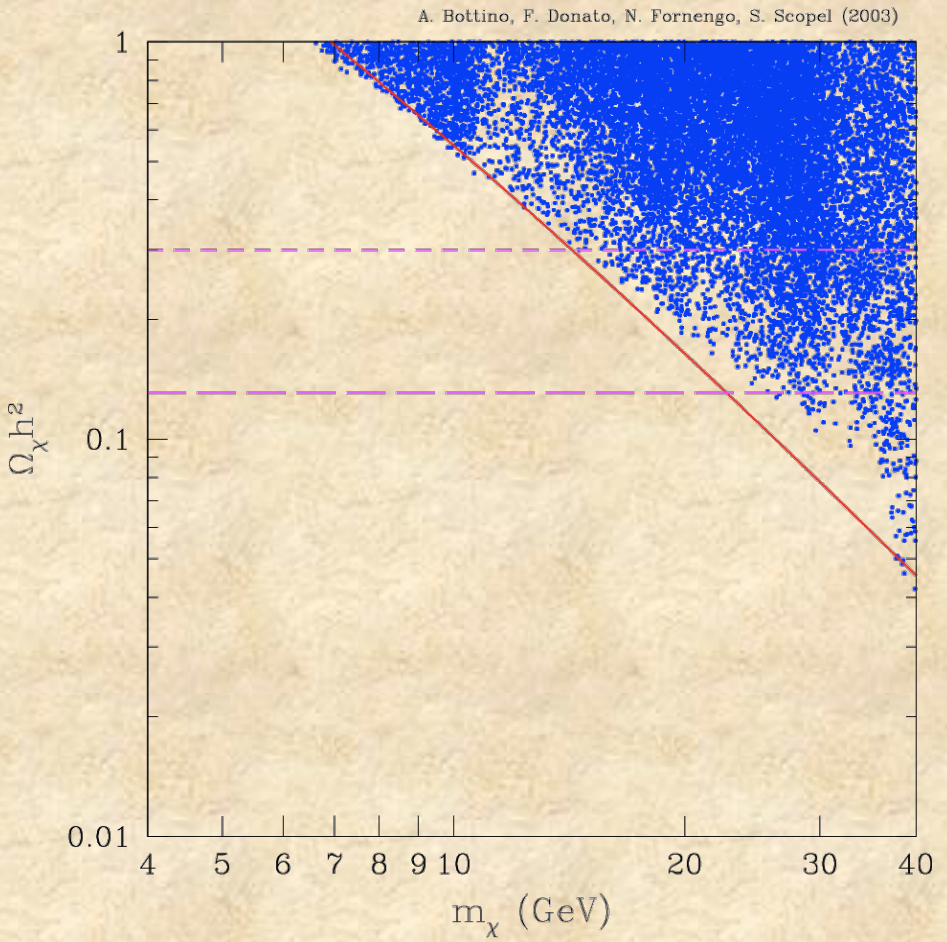
A. Bottino, F. donato, N. Fornengo, S. Scopel, PRD 68 (2008) 043506

Cosmological lower bound on mass

with: $m_A > 90$ GeV



with: $m_A \longrightarrow \infty$



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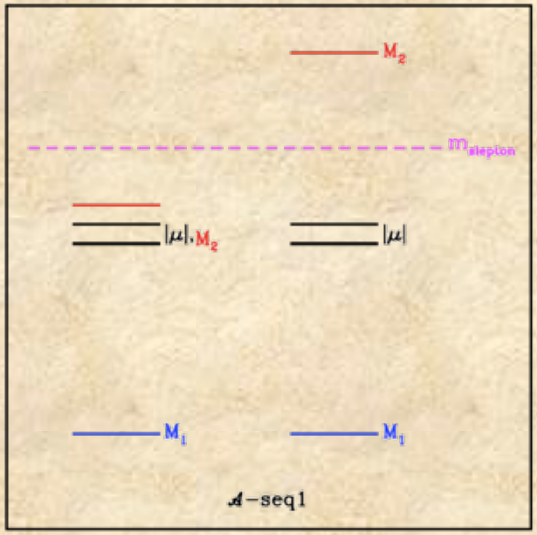
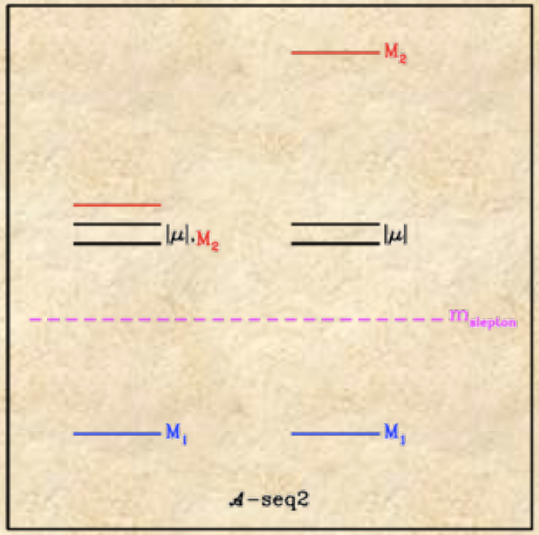
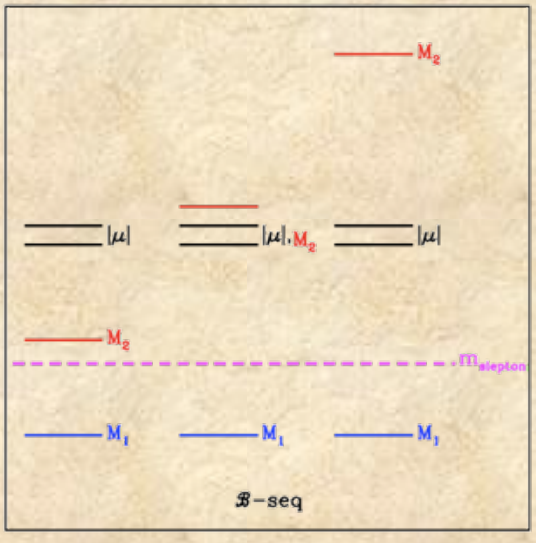
Light neutralinos at LHC: sequential chain



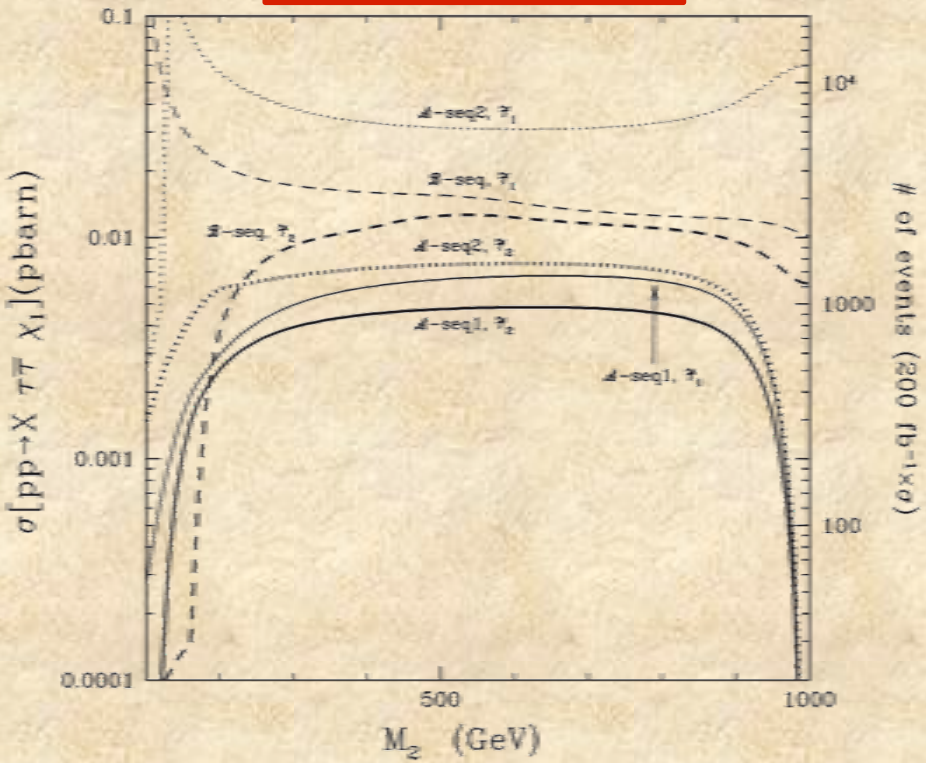




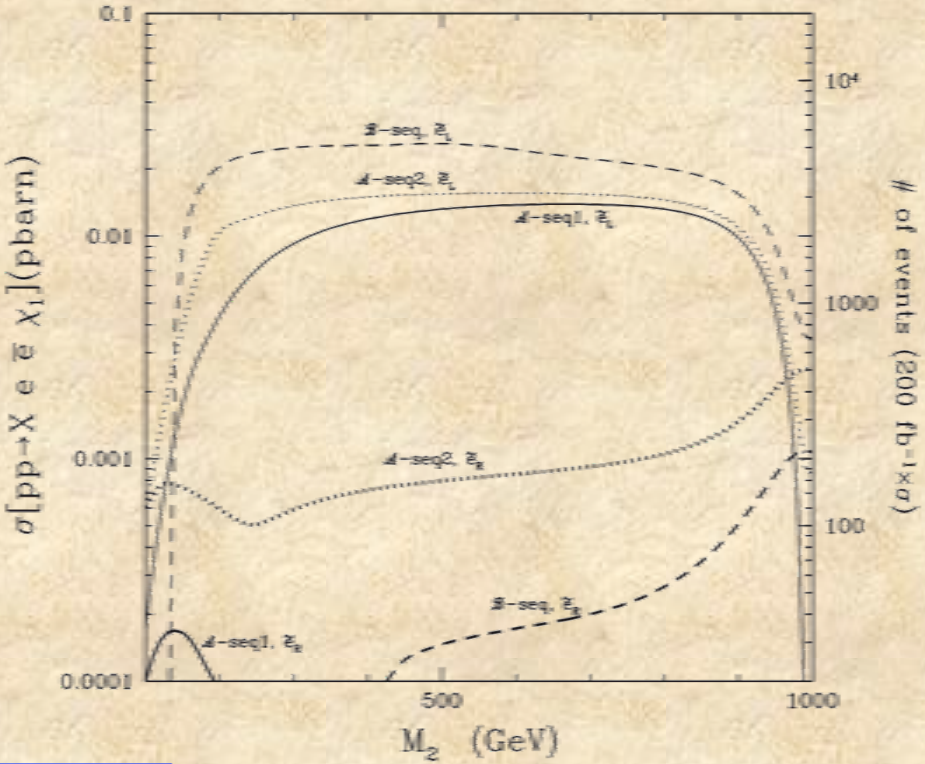
$$\tilde{q} \rightarrow q\chi_i \rightarrow q\tilde{f}f \rightarrow q\bar{f}f\chi_1$$

Sequential chain

$$pp \to X\tau\bar{\tau}\chi_1$$



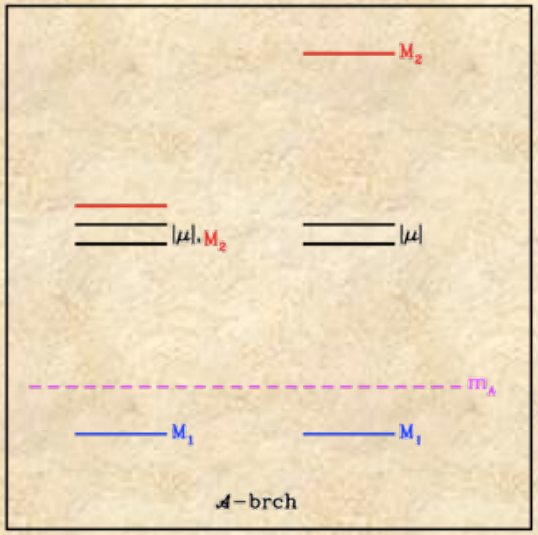
$$pp \to Xe\bar{e}\chi_1$$

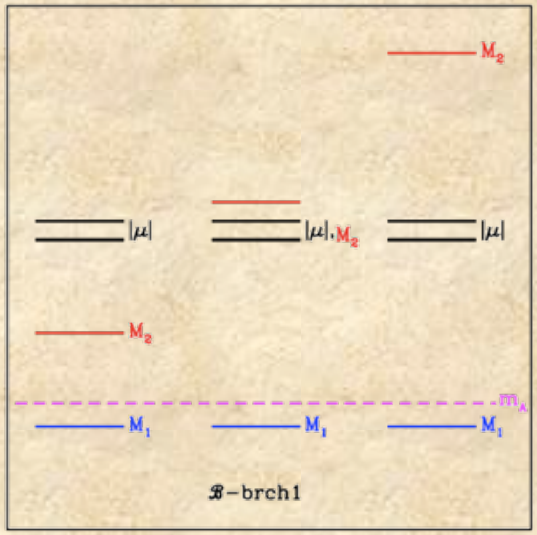


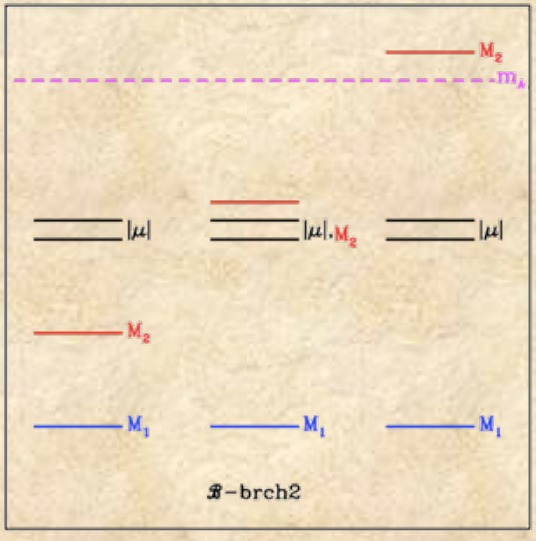
$$\sqrt{s} = 14 \text{ TeV}$$

A. Bottino, N.Fornengo, G. Polesello, S. Scopel, PRD 77 (2008) 115026

Light neutralinos at LHC: branched chain





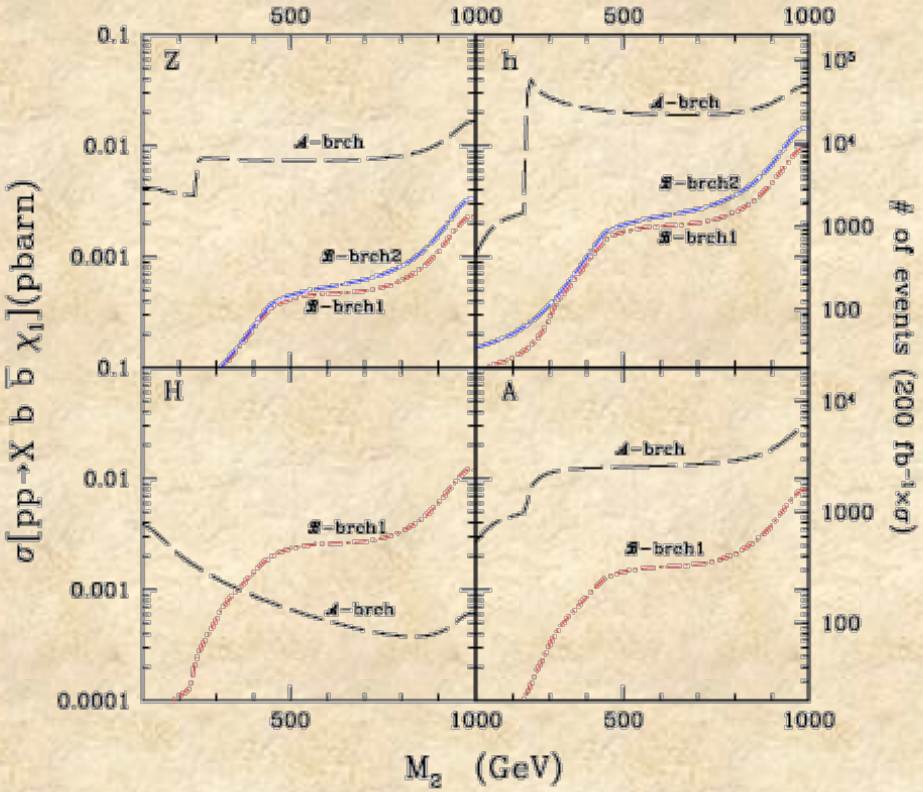


$$\tilde{q} \to q\chi_i \to q(Z, h, H, A)\chi_1 \to q\bar{f}f\chi_1$$

Branched chain

$$pp \to X b \bar{b} \chi_1$$

$$\sqrt{s} = 14 \text{ TeV}$$



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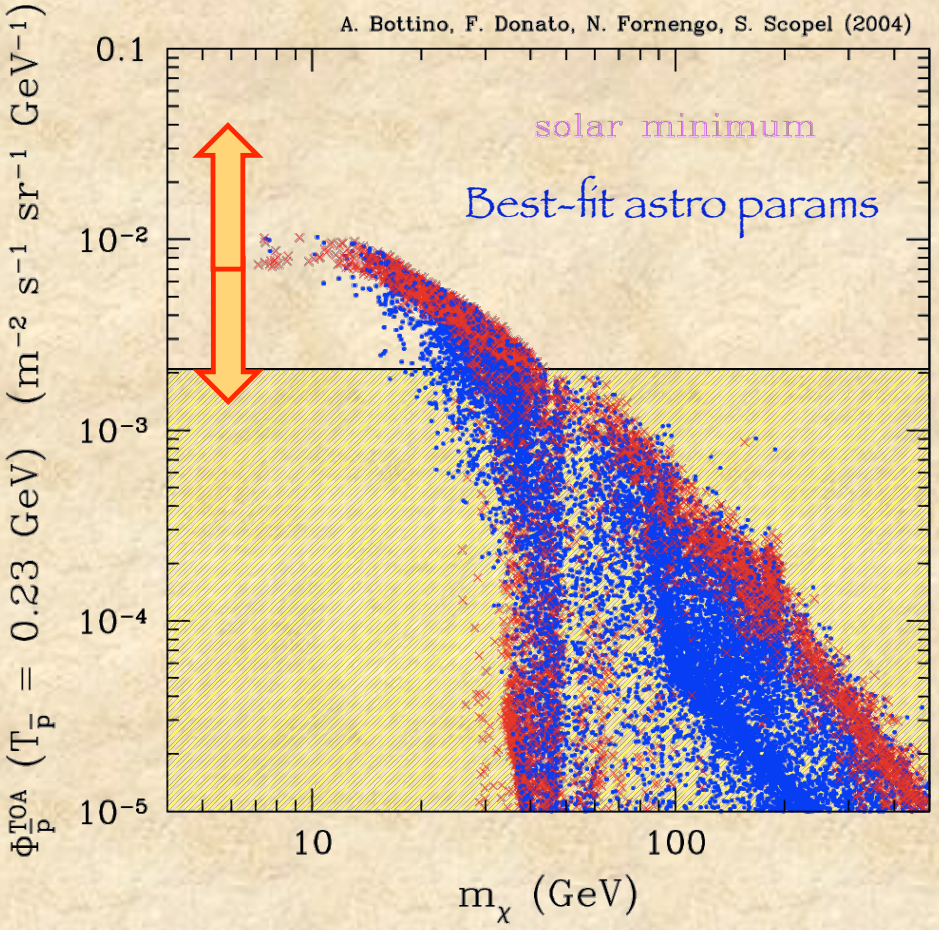
Cosmic antiprotons

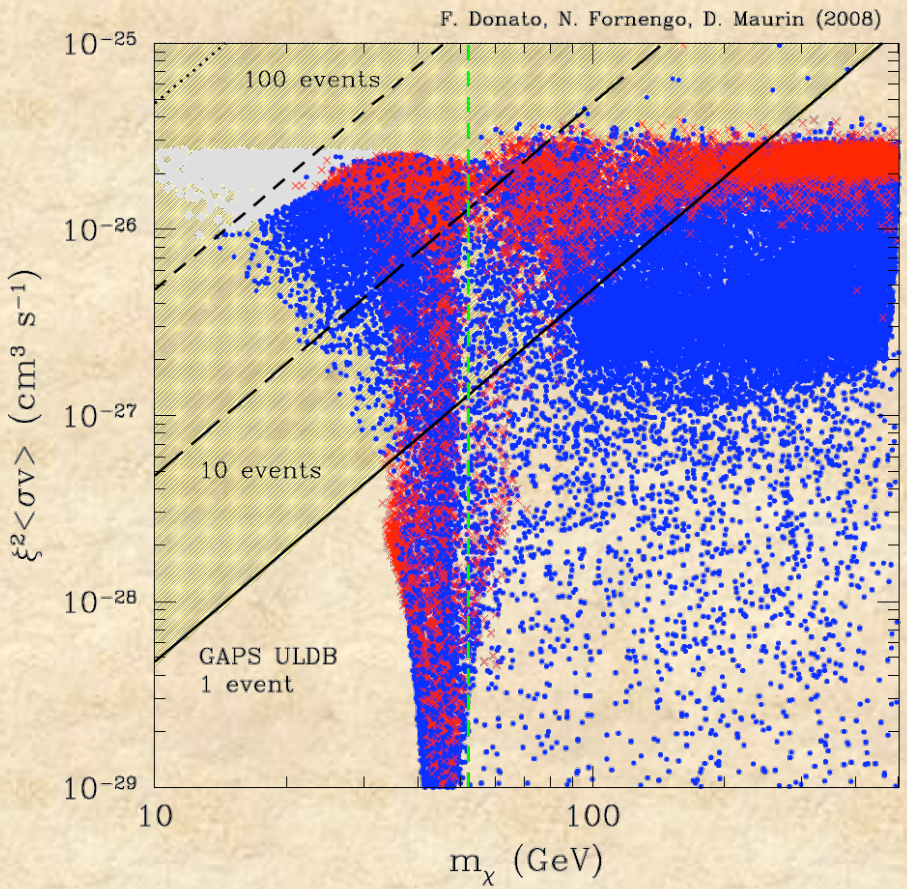
MSSM + gaugino non universal



A. Bottino, F. Donato, N.Fornengo, S. Scopel, PRD 70 (2004) 015005

Cosmic antideuterons

MSSM + gaugino non universal



Best-fit astro params

F. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

Coming data from:

low-background experiments underground

neutrino telescopes

large area detectors

balloon experiments

space detectors

Tevatron, LHC, B Factories

The near future promises to be very exiciting!

(... but life will not be easy ...)