Phenomenological review on dark matter

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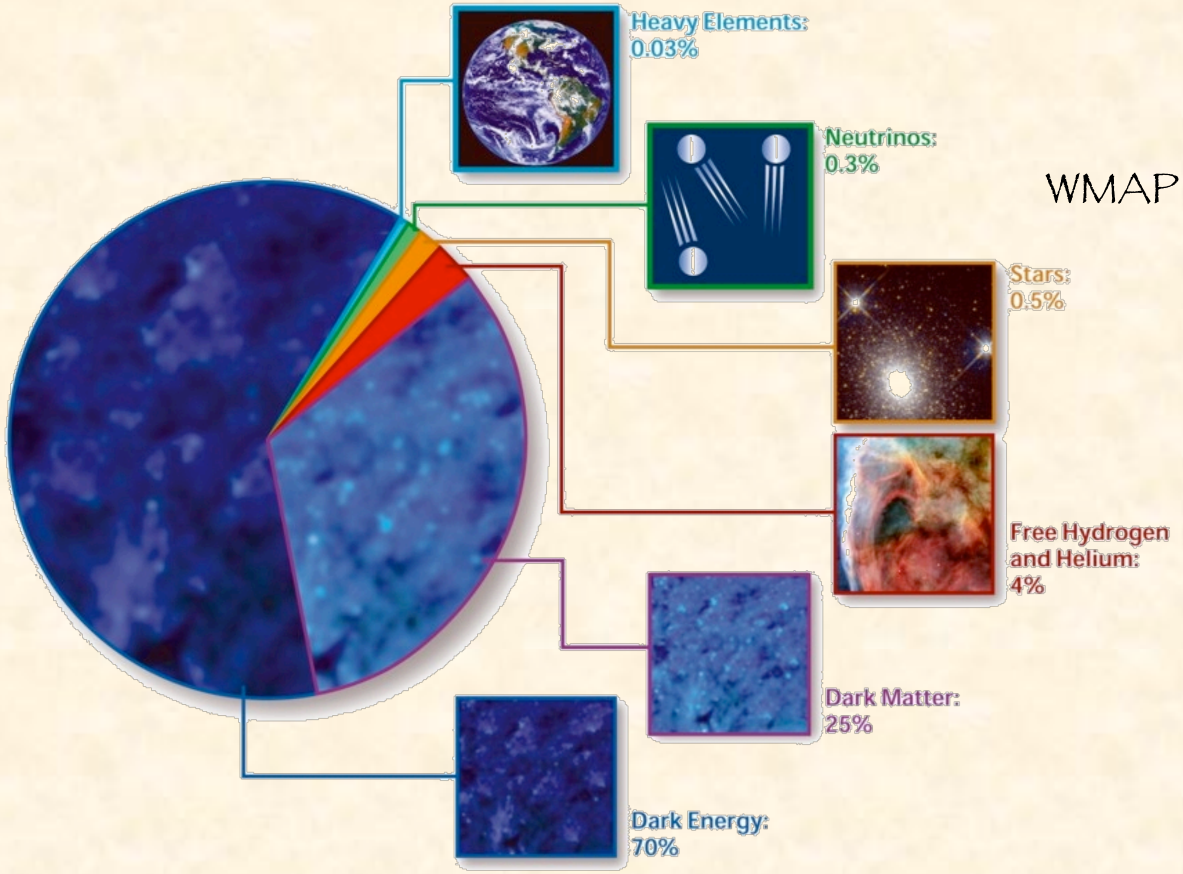
Workshop on the next dark matter experimental research al LNGS (WONDER)

LNGS – 22.03.2010

The Dark Universe



WMAP + SN + BAO + galaxies distribution

Ω_{TOT}	1.0052 ± 0.0064
Ω_Λ	0.721 ± 0.015
Ω_M	0.233 ± 0.013
Ω_b	0.0462 ± 0.0015
h_0	0.701 ± 0.013
$\Omega_M h^2$	0.1369 ± 0.0037
$\Omega_b h^2$	0.02265 ± 0.00059
$\Omega_{DM} h^2$	0.1143 ± 0.0034

E. Komatsu et al., arXiv:0803.0547
J. Dunkley et al., arXiv:0803.0596
G. Hinshaw et al., arXiv:0803.0732

Geometry: the Universe is Flat
Dynamics: the Universe is expanding

- Decelerate for most of its history
- Accelerate since "recent" time and at very "old" times (inflation)

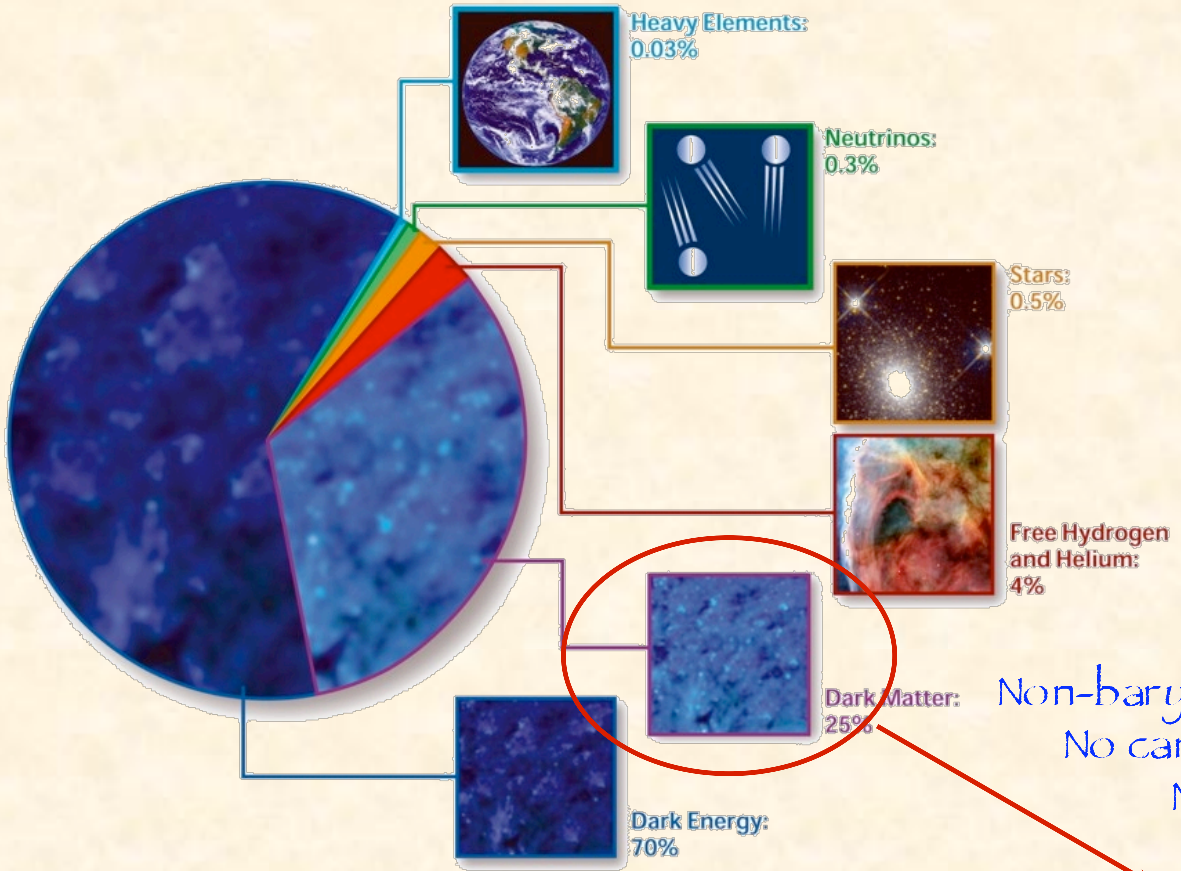
Ω_T CMB temperature anisotropies

Ω_Λ Luminosity distance of high-z SNIa

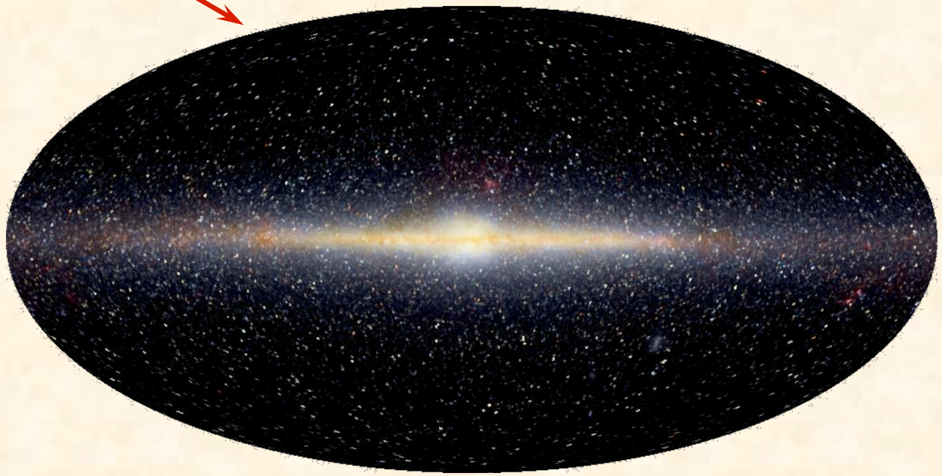
Ω_M Clustered mass abundance

Ω_B Primordial Nucleosynthesis
Amplitude of CMB temperature anisotropies

Dark Matter



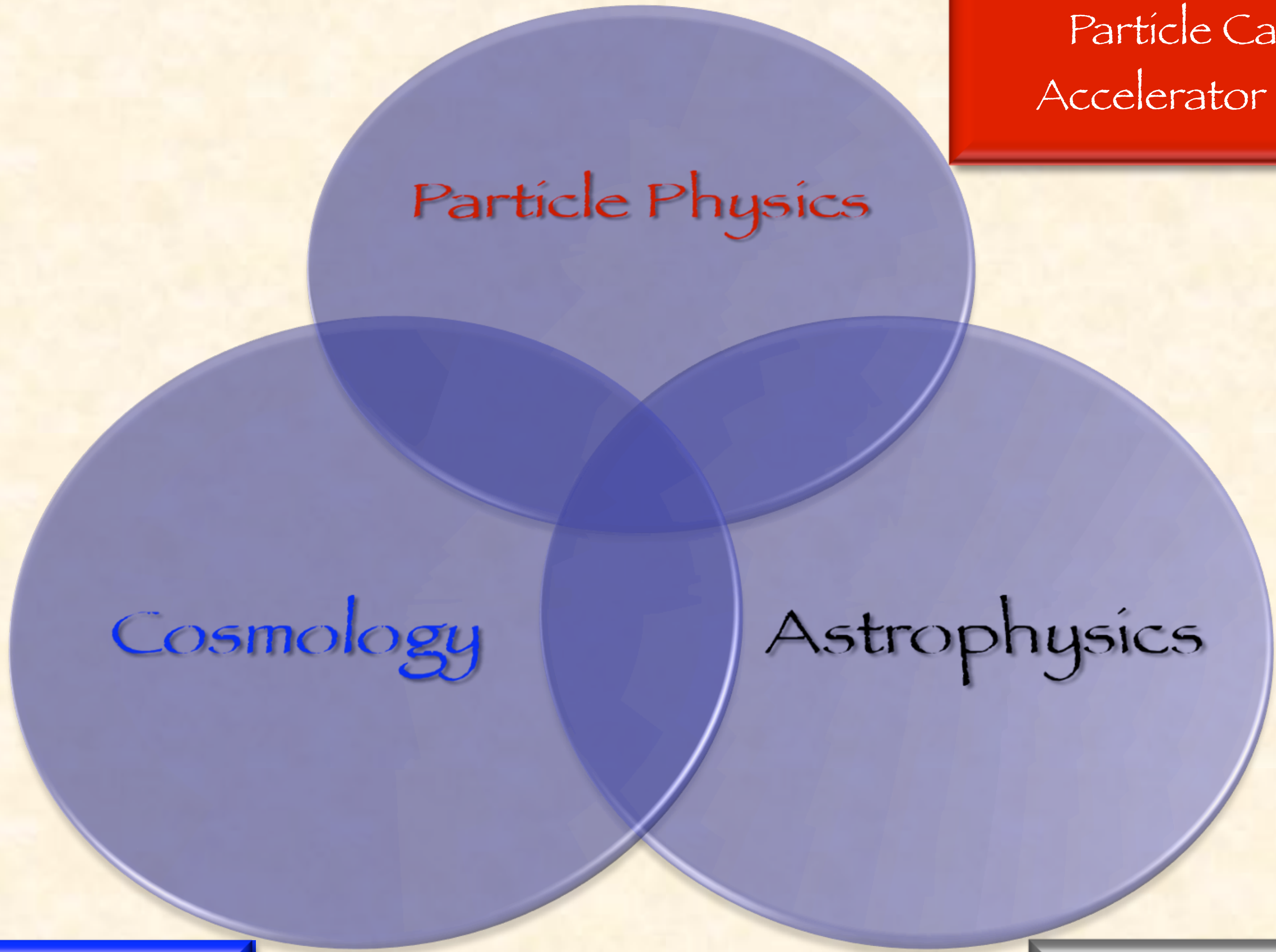
Non-baryonic (cold) dark matter is needed
No candidate in the Standard Model
New fundamental Physics



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

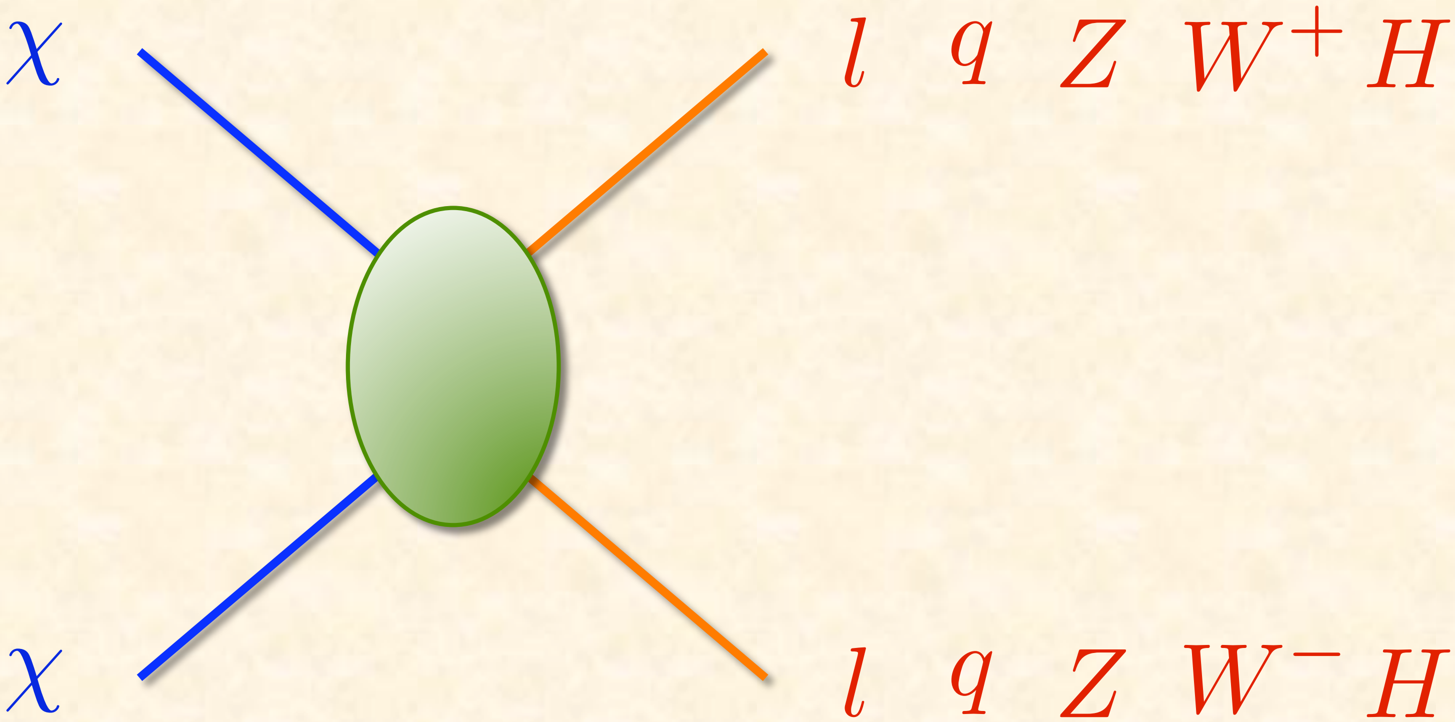
The Particle Dark Matter premise

Particle Candidate
Accelerator Searches



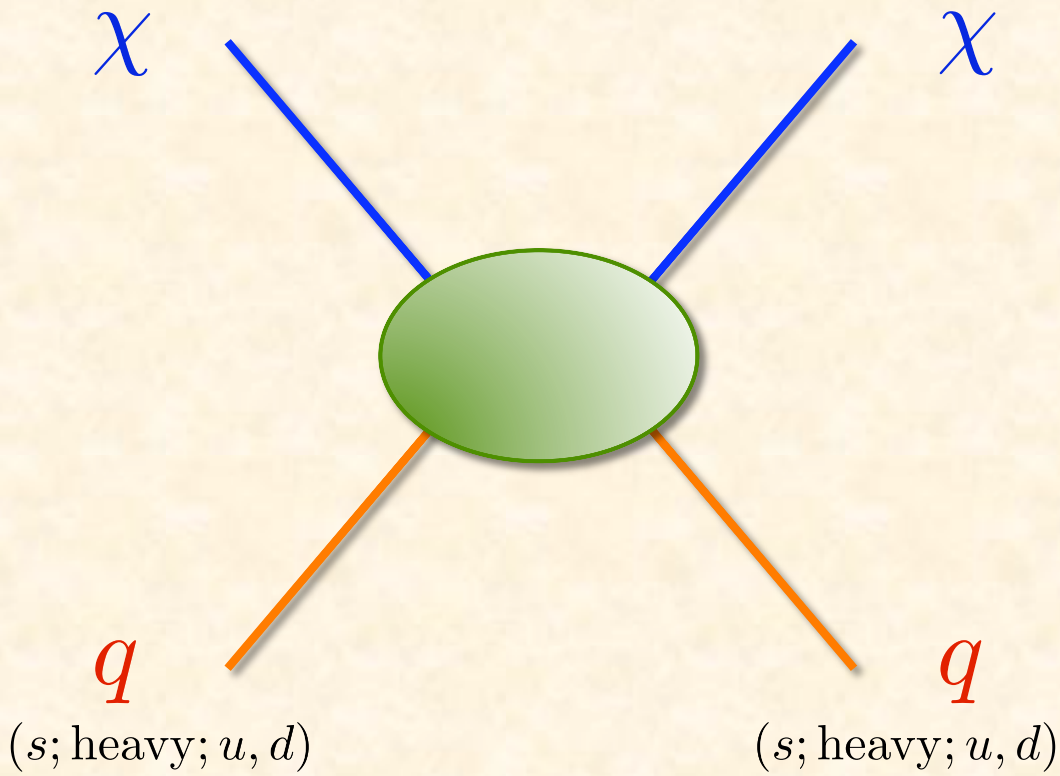
Cosmology of the Particle Candidate

Astrophysical Signals of the Particle Candidate



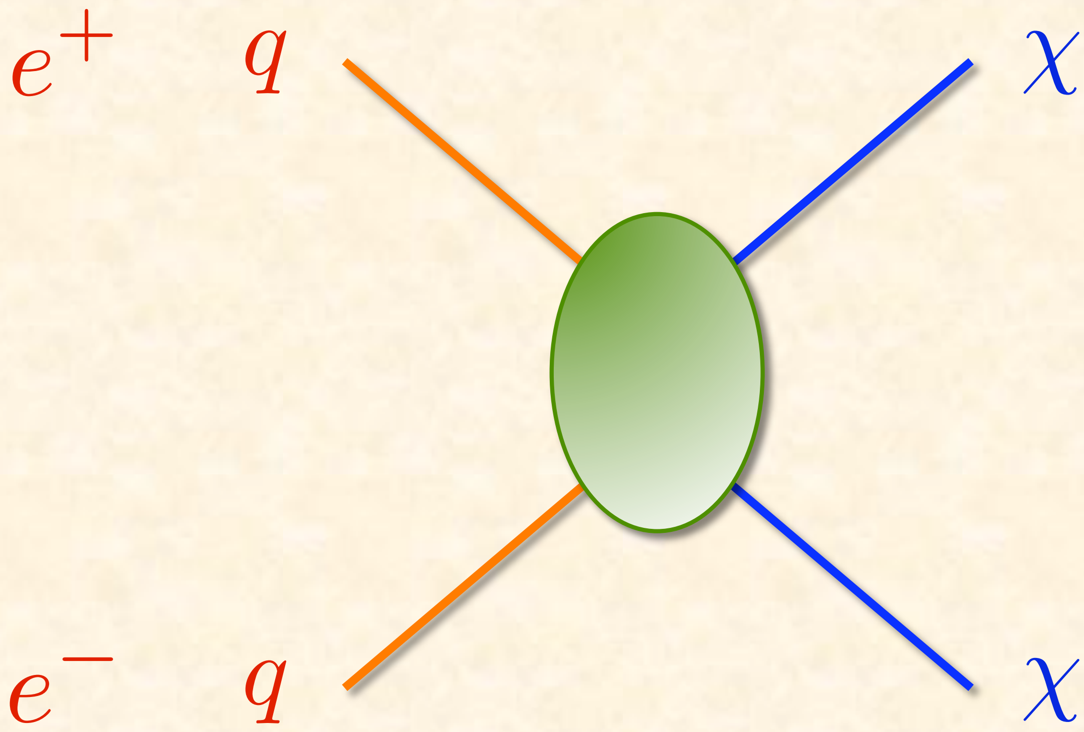
etc

Relic abundance
Indirect signals



Direct detection

Neutrinos from Earth and Sun



+ other NP states

Accelerator searches

The Particle Physics Model

Non-baryonic DM candidates

- Non supersymmetric candidates
  - Neutrino: standard, RH MeV, (…)
  - “Minimal” candidates (e.g.: MDM)
  - 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
  - (…)

Neutralino →

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

Non-baryonic DM candidates

- Non supersymmetric candidates
  - Neutrino: standard, RH MeV, (…)
  - "Minimal" candidates (e.g.: MDM)
  - 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

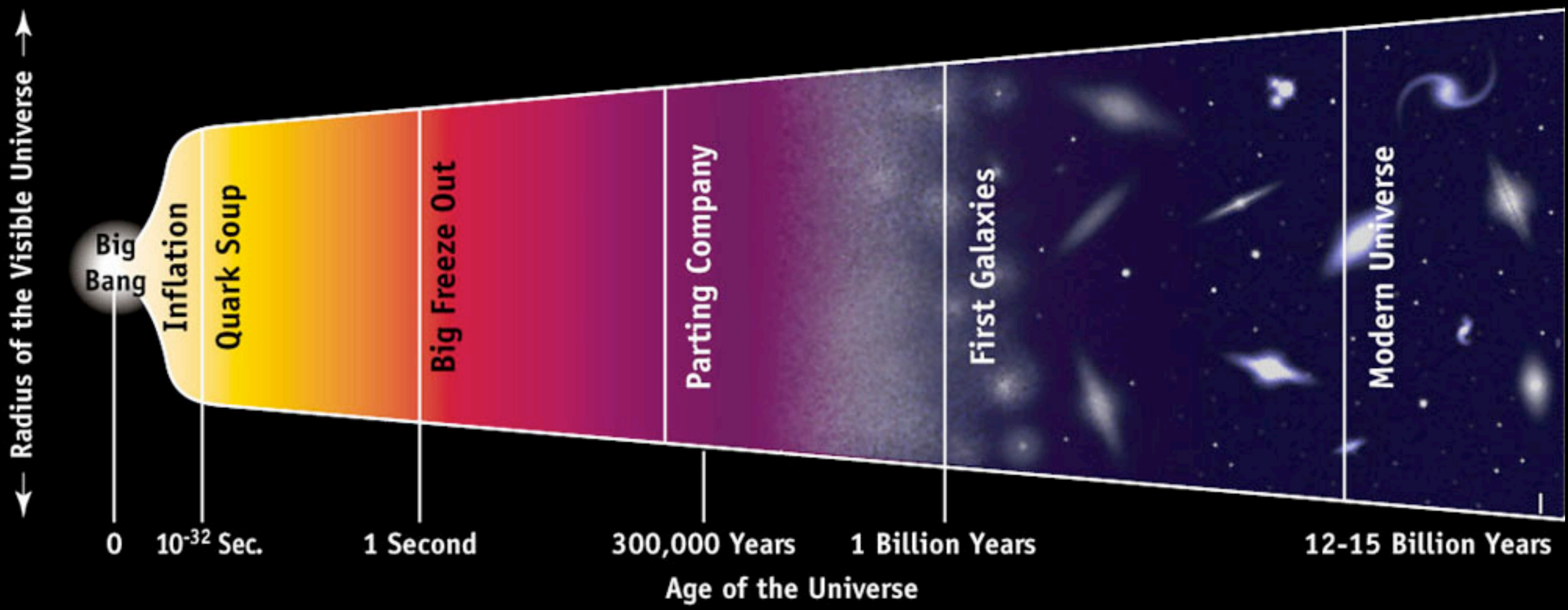
  (…)

Sneutrino:

- With R-handed (s)neutrino
- With Majorana mass terms
- In see-saw models
- NMSSM
- (…)

C. Arina, N. Fornengo, JHEP 0711 (2007) 029
C. Arina et al., PRL 101 (2008) 161802
D. Cerdeno et al., PRD 79 (2009) 023510
D. Cerdeno et al., arXiv:0903.4677 [hep-ph]
R. Allahverdi et al., PLB 677 (2009) 172
R. Allahverdi et al., arXiv:0907.1486
D. Demir et al., arXiv:0906.3540
(…)

The Cosmological Context



Dark Matter formation

Particle DM formation

- Thermal relic

$$\Omega h^2 \sim \langle \sigma v \rangle_{\rm ann}^{-1} \longrightarrow \langle \sigma v \rangle_{\rm ann} = 3 \cdot 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

unless coannihilation occurs

- Thermal relic with non-standard cosmology

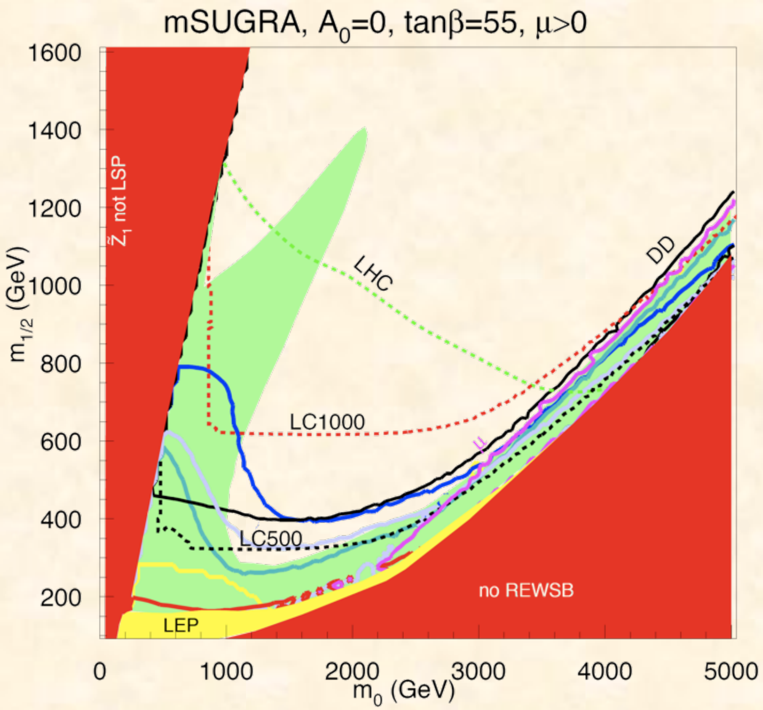
$\Omega h^2 \sim \langle \sigma v \rangle_{\rm ann}^{-1}$ with $\langle \sigma v \rangle_{\rm ann} \neq \langle \sigma v \rangle_{\rm ann}^{\rm GR}$

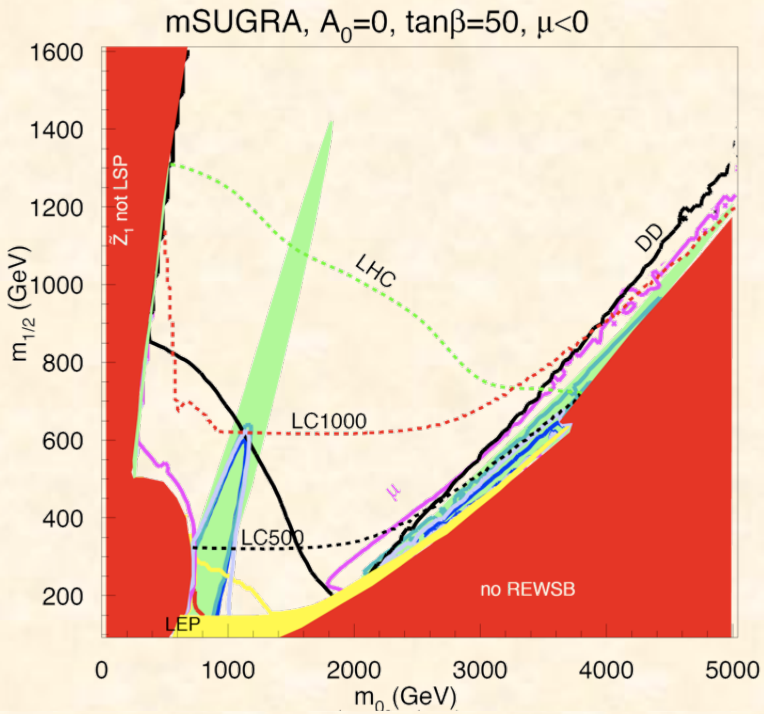
- Non-thermal relic
  - In a low-reheating cosmology
  - From next-to-lightest particle decay
- (...)

Minimal Supergravity

mSUGRA: few parameters, very constrained

Non-universal SUGRA: some more parameter, (somehow) less constrained





$$M_{1/2} \quad m_0 \quad A_0 \quad \tan\beta \quad \mathrm{sign}(\mu)$$

$$(\delta_{H_i} \quad \delta_{\tilde{q}_j} \quad \delta_{\tilde{l}_k})$$

H. Baer, 0901.4732 [hep-ph]

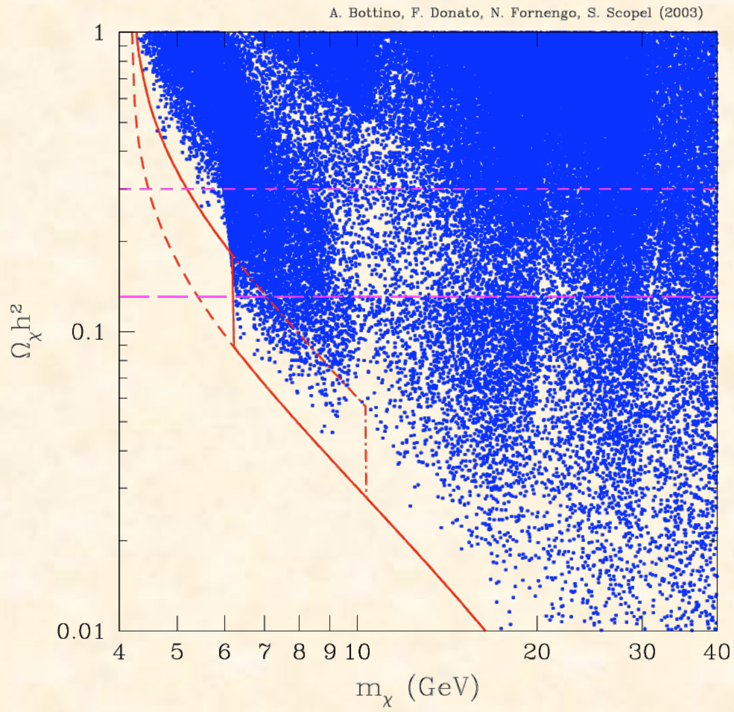
MSSM

MSSM at the EW scale: more parameters, grabs a richer phenomenology

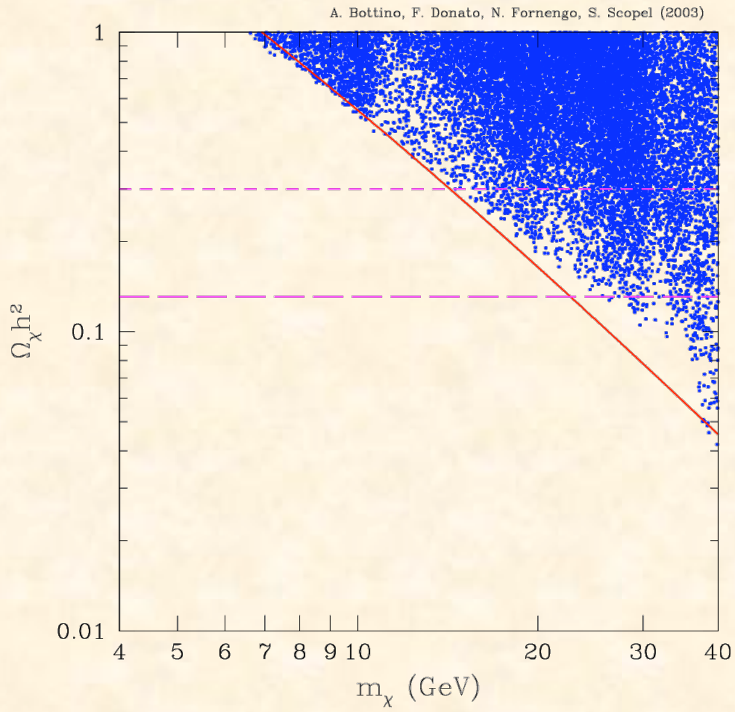
$$M_1 \quad M_2 \quad \mu \quad \tan\beta \; m_A \; m_{\tilde{q}_i} \; m_{\tilde{l}_j} \;\; A_k$$

MSSM + Gaugino non-universality

MSSM at the EW scale: more parameters, grabs a richer phenomenology
MSSM + non-universality between M_1 and M_2: light neutralinos



with: $m_A > 90$ GeV



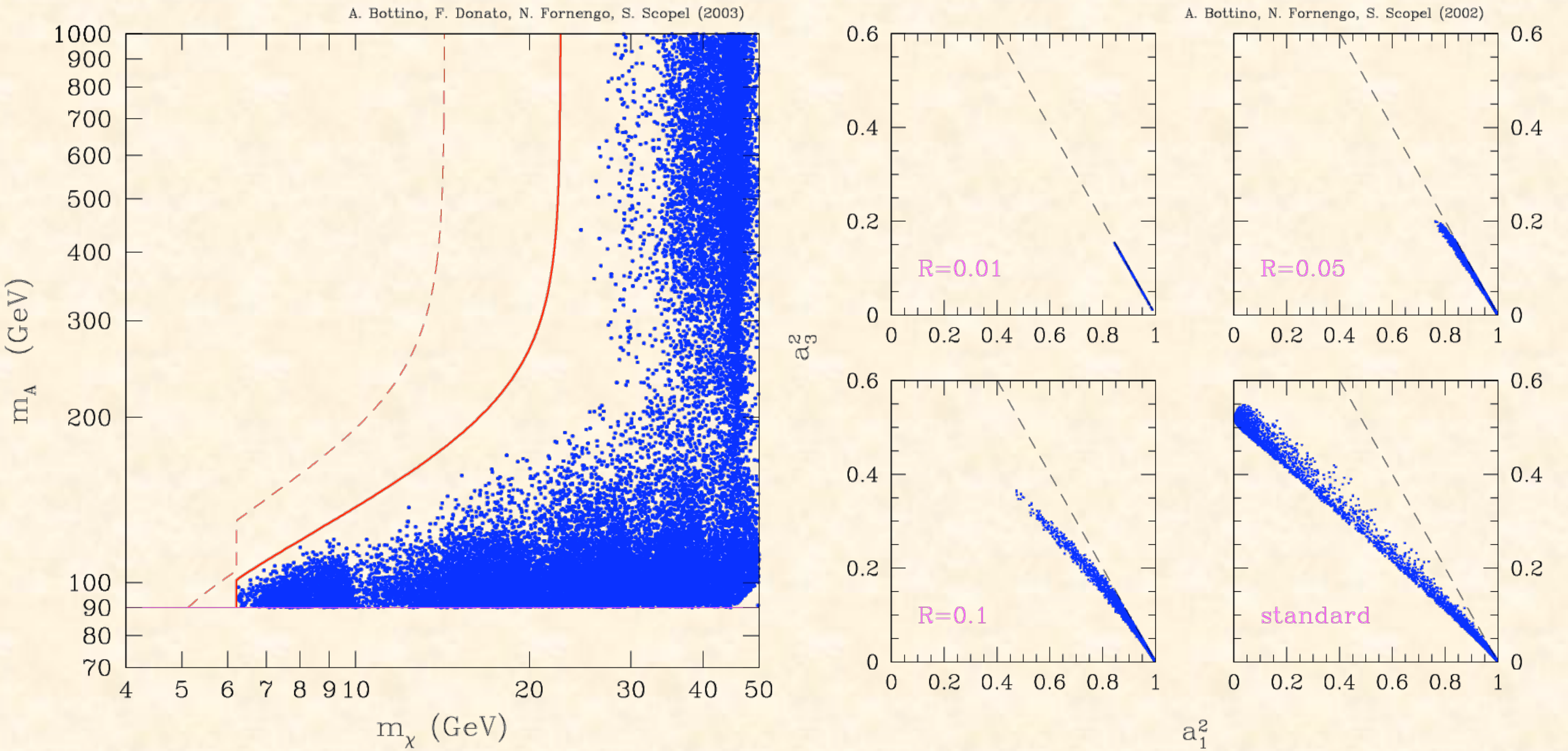
with: $m_A \longrightarrow \infty$

$$M_1 \quad M_2 \quad \mu \quad \tan\beta \; m_A \; m_{\tilde{q}_i} \; m_{\tilde{l}_j} \; A_k$$

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

MSSM + Gaugino non-universality

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



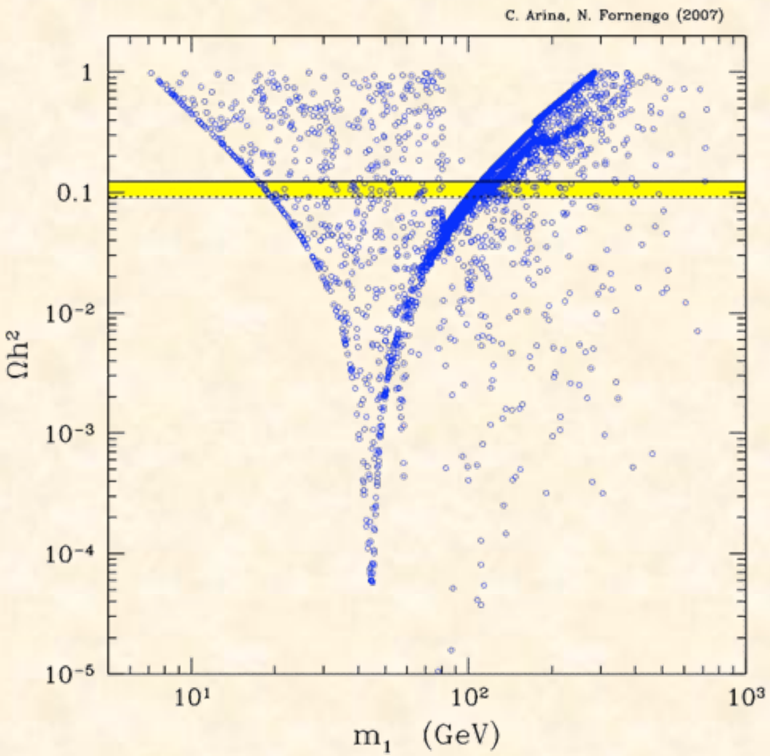
Light Neutralino LSP: almost pure bino + fraction of higgsino

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

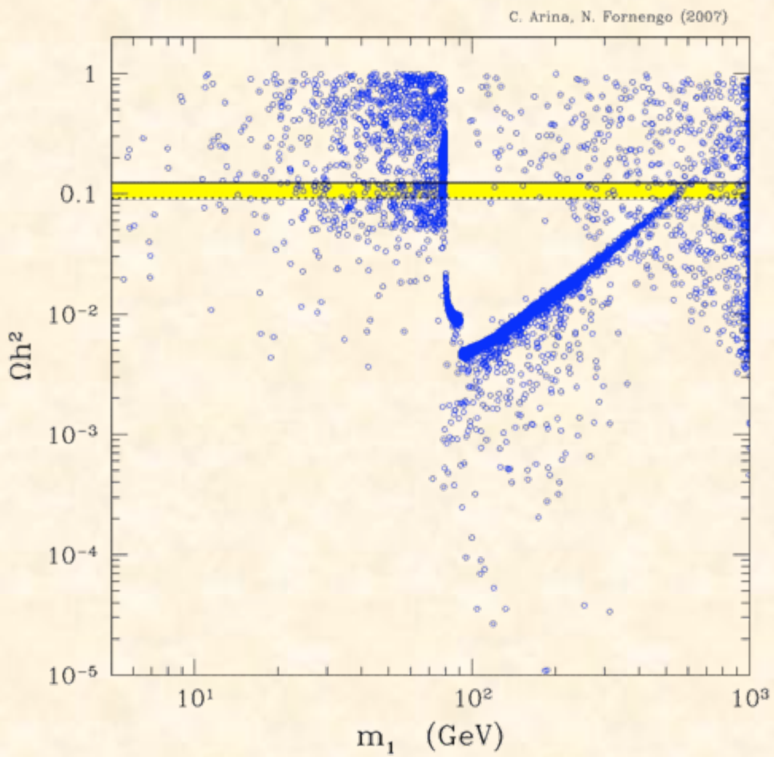
Sneutrino dark matter

MSSM at the EW scale with terms wich induce neutrino masses

(May) Address DM + neutrino mass in the same sector



Left+Right models

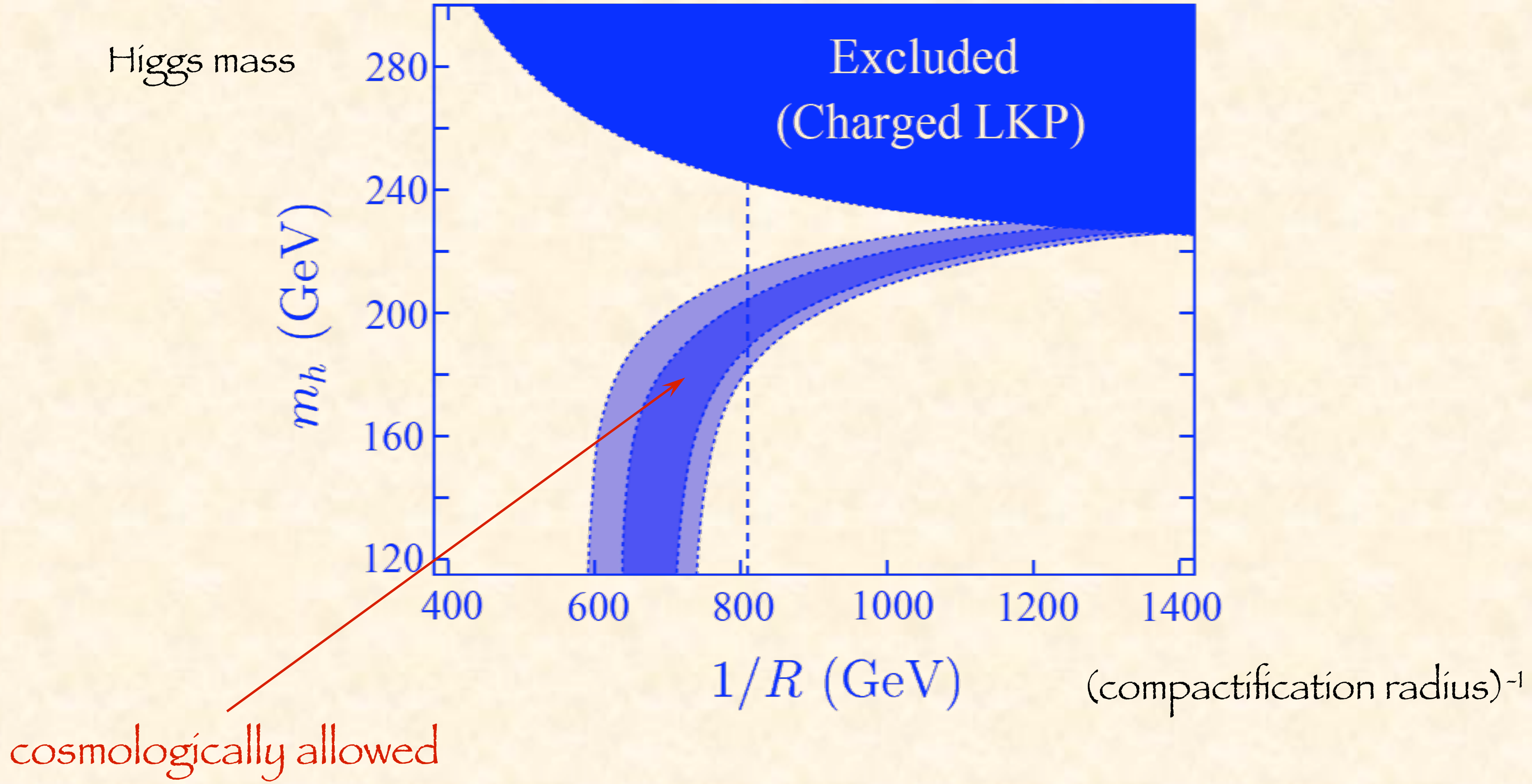


"Majorana" models

C. Arina, N. Fornengo, JHEP 0711 (2007) 029

Universal extra-dimension theories

In the simplest realization (UED): few parametrers



Kakizaki, Matsumoto, Senami, PRD 74 (2006) 023504
See also: Servant, Tait, NPB 650 (2003) 391

(Extra)Galactic Dark Matter Signals

Galactic Dark Matter

CDM in galaxies:

- DM as a non-baryonic particle
- 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
- Exploit (anti) correlations among signals
- 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)

Direct detection

Interaction mechanisms - WIMPs

- Elastic scattering with nuclei
  - Ex.: Neutralino, Sneutrinos, KK

$$\chi\, \mathcal{N} \longrightarrow \chi\, \mathcal{N}$$

E_R > few KeV

- Inelastic scattering with nuclei

Tucker-Smith, Weiner, PRD 64 (2001) 043502

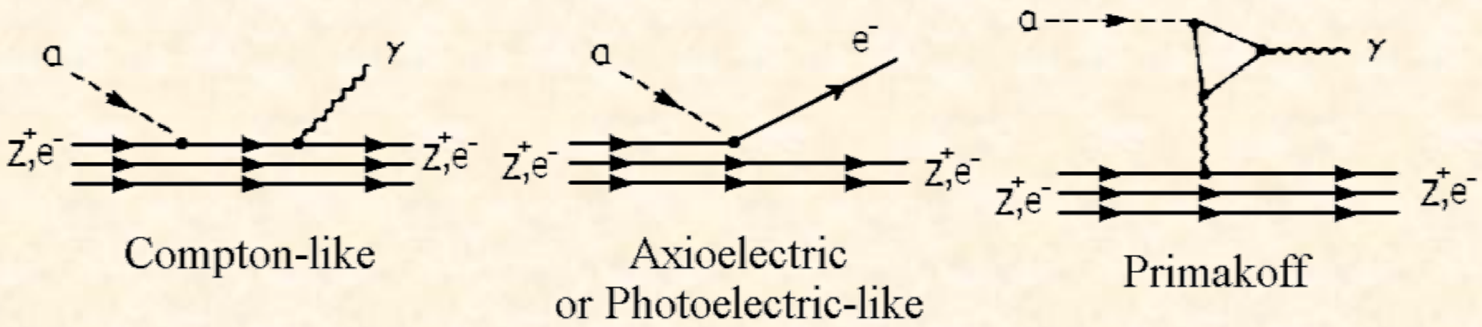
$$\chi\, \mathcal{N} \longrightarrow \chi'\, \mathcal{N}$$

Scatter if: $\Delta m < \dfrac{\beta^2 m_1 m_{\mathcal{N}}}{2(m_1 + m_{\mathcal{N}})}$ about 1-100 KeV

  - Ex.: Sneutrinos

Interaction mechanisms – non WIMPs

- Inelastic, scatter on electrons
  - Ex.: Light (KeV) [pseudo]scalars



WIMPs - Scattering cross section

- Spin-independent
  - Cross section proportional to the (mass number)^2 of the nucleus
  - Channels:
    - Vector boson (Z)-mediated: gauge-type, well known
    - Scalar (H, squarks)-mediated: large hadronic uncertainties

$$I_{h,H} = \sum_q k_q^{h,H} m_q \langle N|\bar{q}q|N\rangle = k_{u-\text{type}}^{h,H}\, g_u + k_{d-\text{type}}^{h,H}\, g_d$$

(in MeV)	$m_l < N\|\bar{q}_l q_l\|N >$	$m_s < N\|\bar{s}s\|N >$	$m_h < N\|\bar{h}h\|N >$	g_u	g_d
Set A	27	131	56	139	214
Set B	28	186	52	132	266
Set C	37	456	30	97	523

  - Nuclear form factors

- Spin-dependent
  - Cross section proportional to the (spin)^2 of the nucleus
  - Spin form factors

Interaction rate (WIMP - scalar)

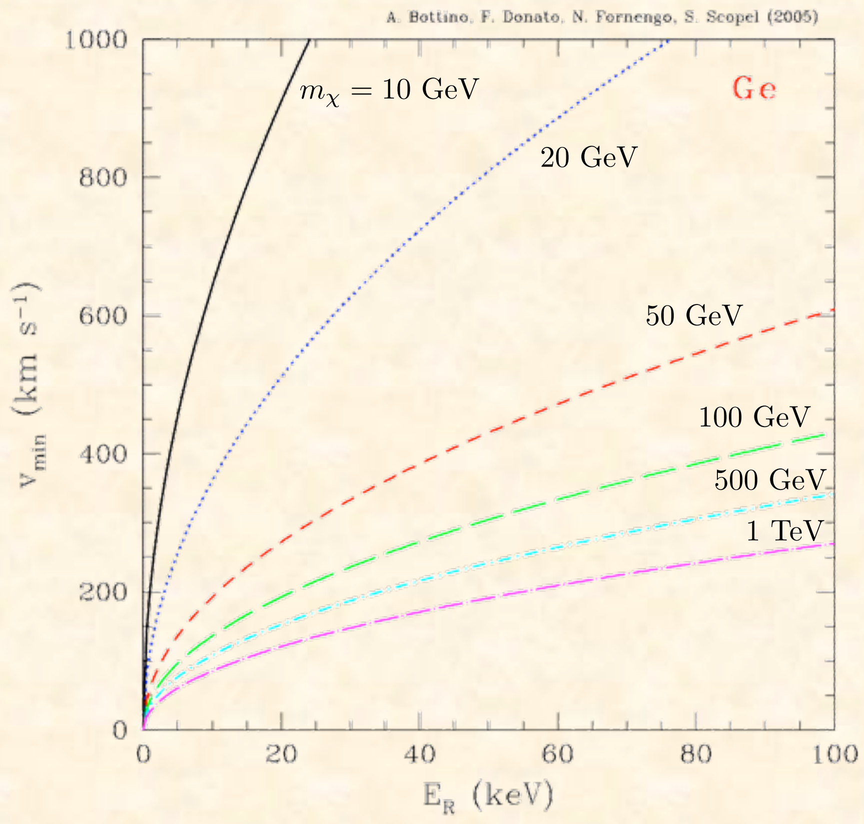
$$\frac{dR}{dE_R} = N_T \, \frac{\rho_0}{m_\chi} \, \frac{m_N}{2\mu_1^2} \, A^2 \, [\xi \sigma_{\rm scalar}^{\rm (nucleon)}] \, F^2(E_R) \, \mathcal{I}(v_{\rm min})$$

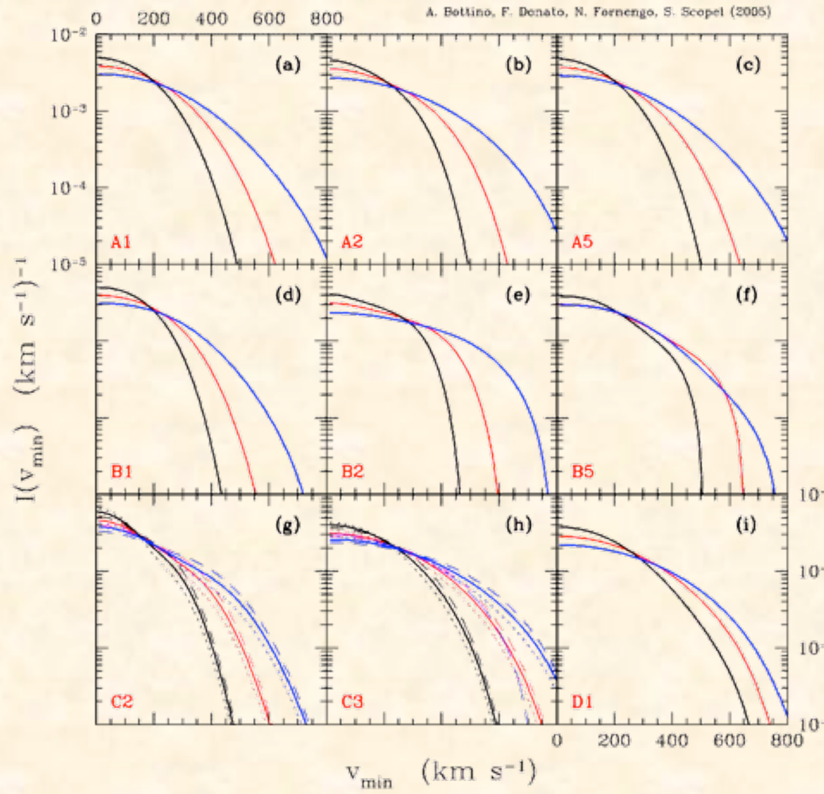
$$\mathcal{I}(v_{\rm min}) = \int_{w \geq v_{\rm min}} d^3 w \; \frac{f_{\rm ES}(\vec{w})}{w}$$

$$f_{\rm ES}(\vec{w}) = f(\vec{w} + \vec{v}_\oplus)|_{[v_{\rm rot};v_{\rm esc}]}$$

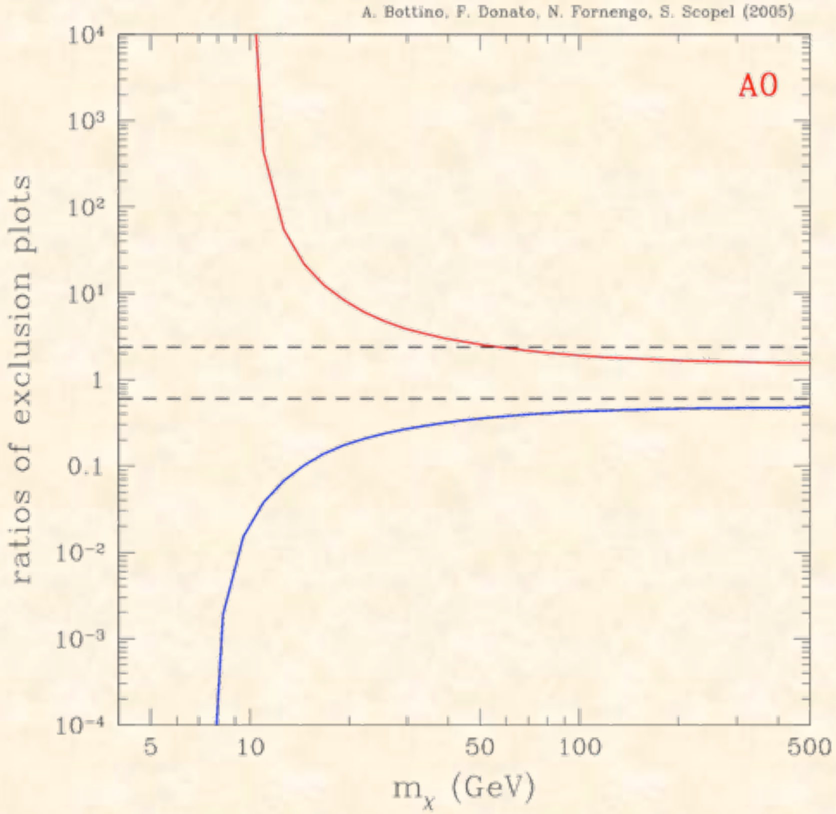
$$v_{\rm min} = [m_N E_R / (2\mu_A^2)]^{1/2}$$

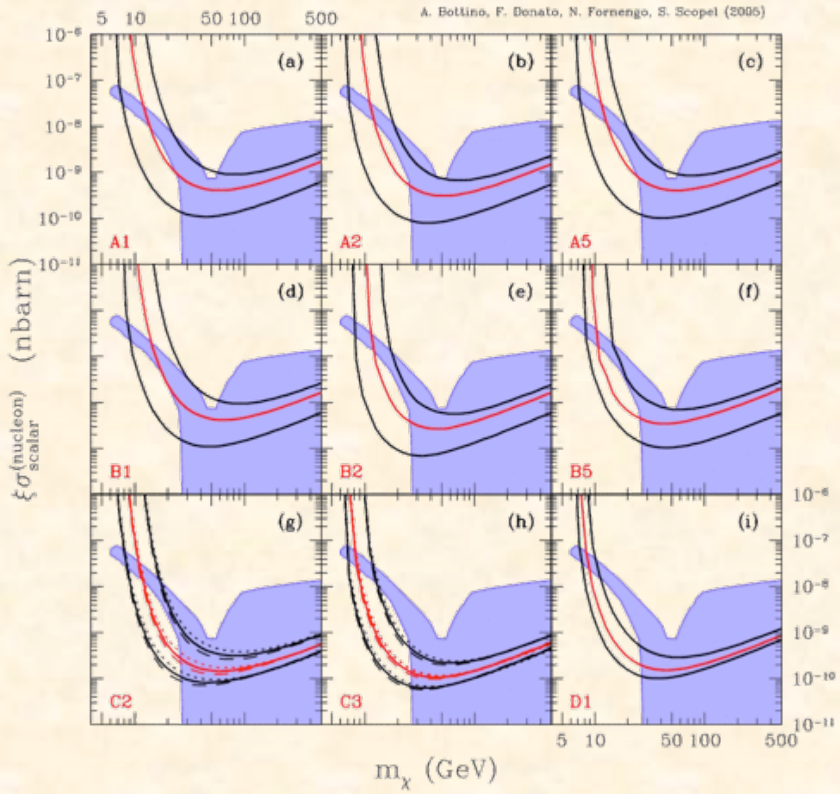
Response function





Bounds


A. Bottino, F. Donato, N. Fornengo, S. Scopel (2005)
A0
ratios of exclusion plots
m_χ (GeV)


A. Bottino, F. Donato, N. Fornengo, S. Scopel (2005)
(a) (b) (c) (d) (e) (f) (g) (h) (i)
A1 A2 A5 B1 B2 B5 C2 C3 D1
$\xi\sigma^{(nucleon)}_{scalar}$ (nbarn)
m_χ (GeV)

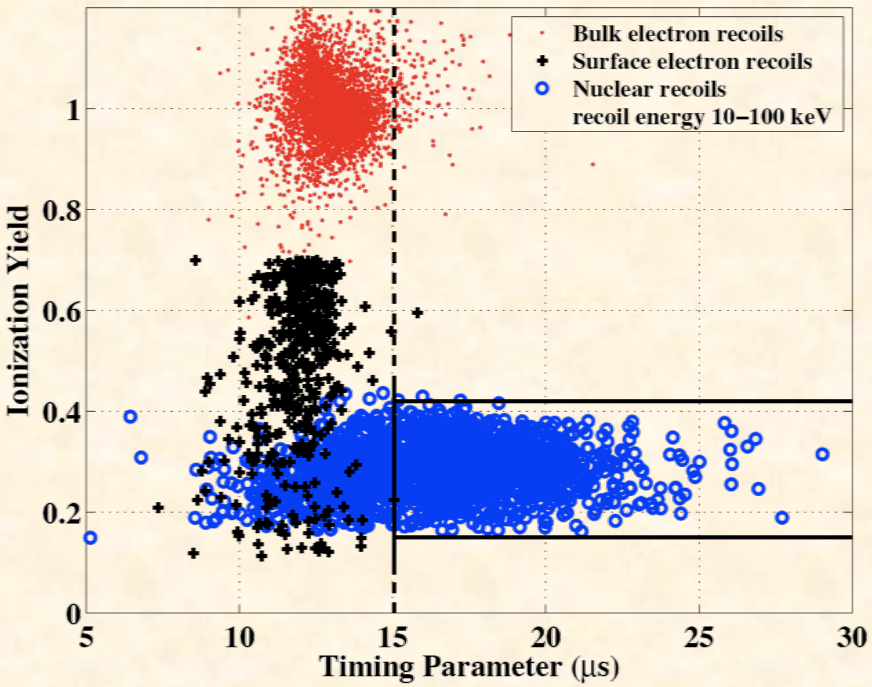
Direct detection experiments

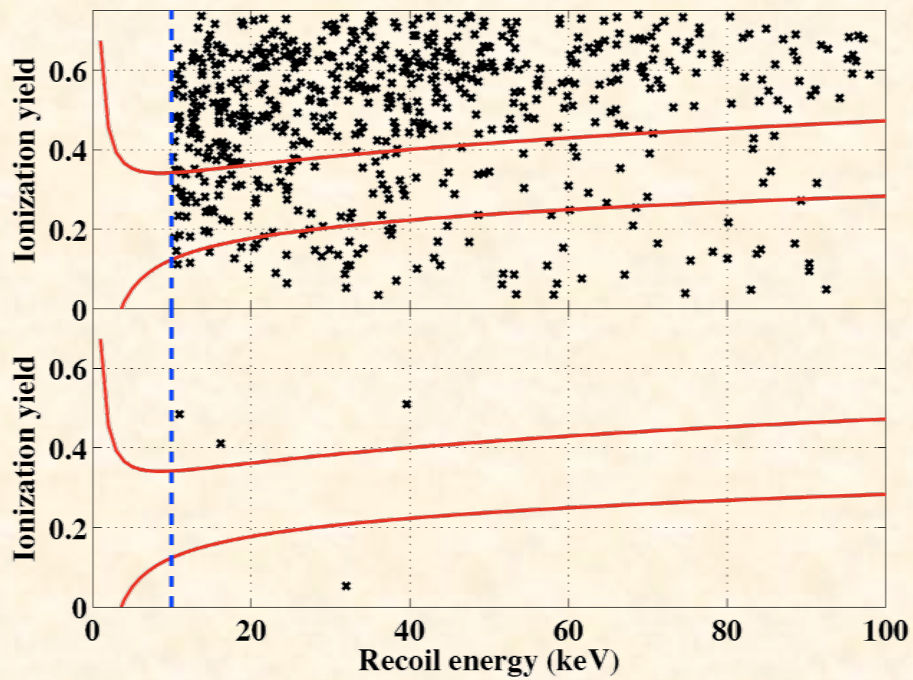
- Background-rejection experiment
  - Do not exploit a specific signature of the signal
  - Rely on reduction/interpretation of background

- Annual modulation experiment (DAMA)
  - Exploits a specific signature
  - Highly stable over long periods

CDMS II - 2008

– Ionization yield: rejection factor > 10^4
– Signal Timing: brings rejection factor > 10^6



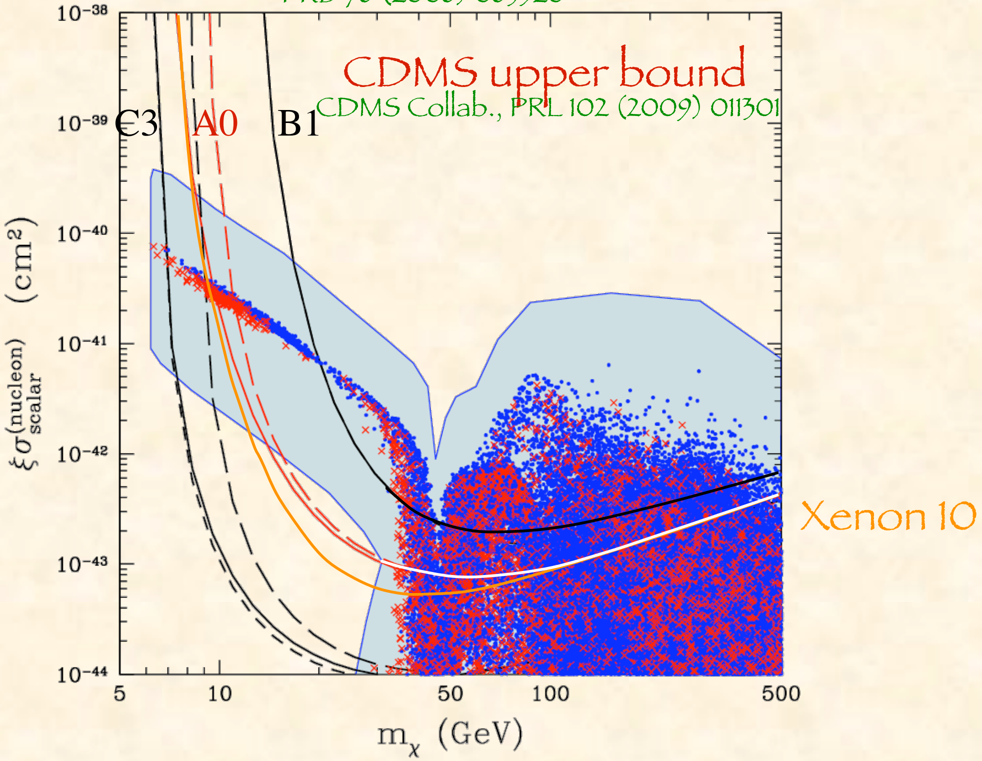


Z. Ahmed (CDMS Collab.), PRL 102 (2009) 011301

Upper limits from bckg-rejection experiments

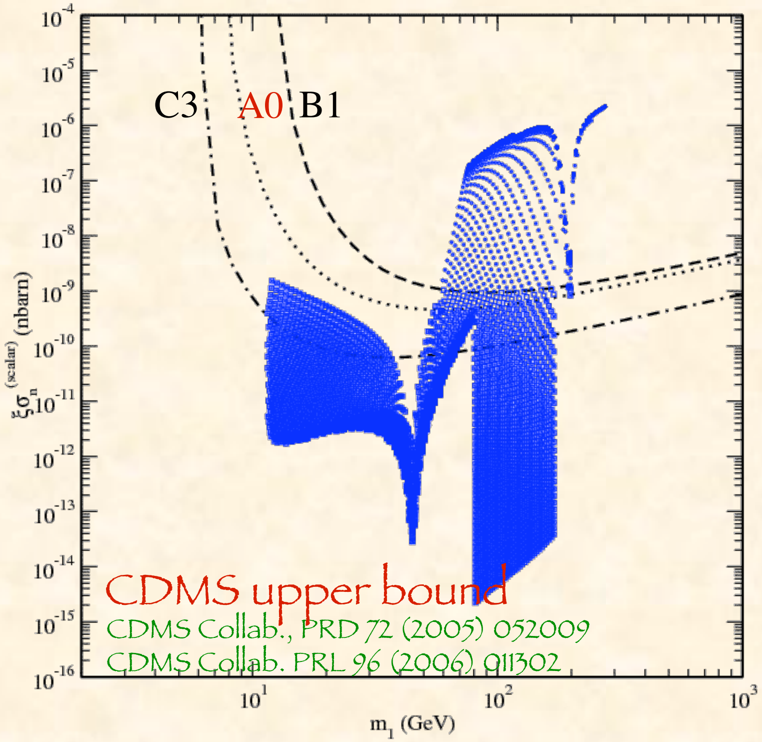
Neutralino DM
MSSM + gaugino non universal

Bottino, F. Donato, N. Fornengo, S. Scopel, PRD 78 (2008) 083520



Sneutrino DM in LR models

C. Arina, N. Fornengo, JHEP 0711:029,2007



A0	isothermal sphere	$\rho_l = 0.3$ GeV cm^{-3}	min halo
B1	spherical halo w/ non isotropic $\vec{v}$ DF	$\rho_l = 0.2$ GeV cm^{-3}	min halo
C3	axisymmetric halo	$\rho_l = 1.66$ GeV cm^{-3}	max halo

Typical signatures of direct detection

Annual modulation

Diurnal modulation

Directionality of the recoil

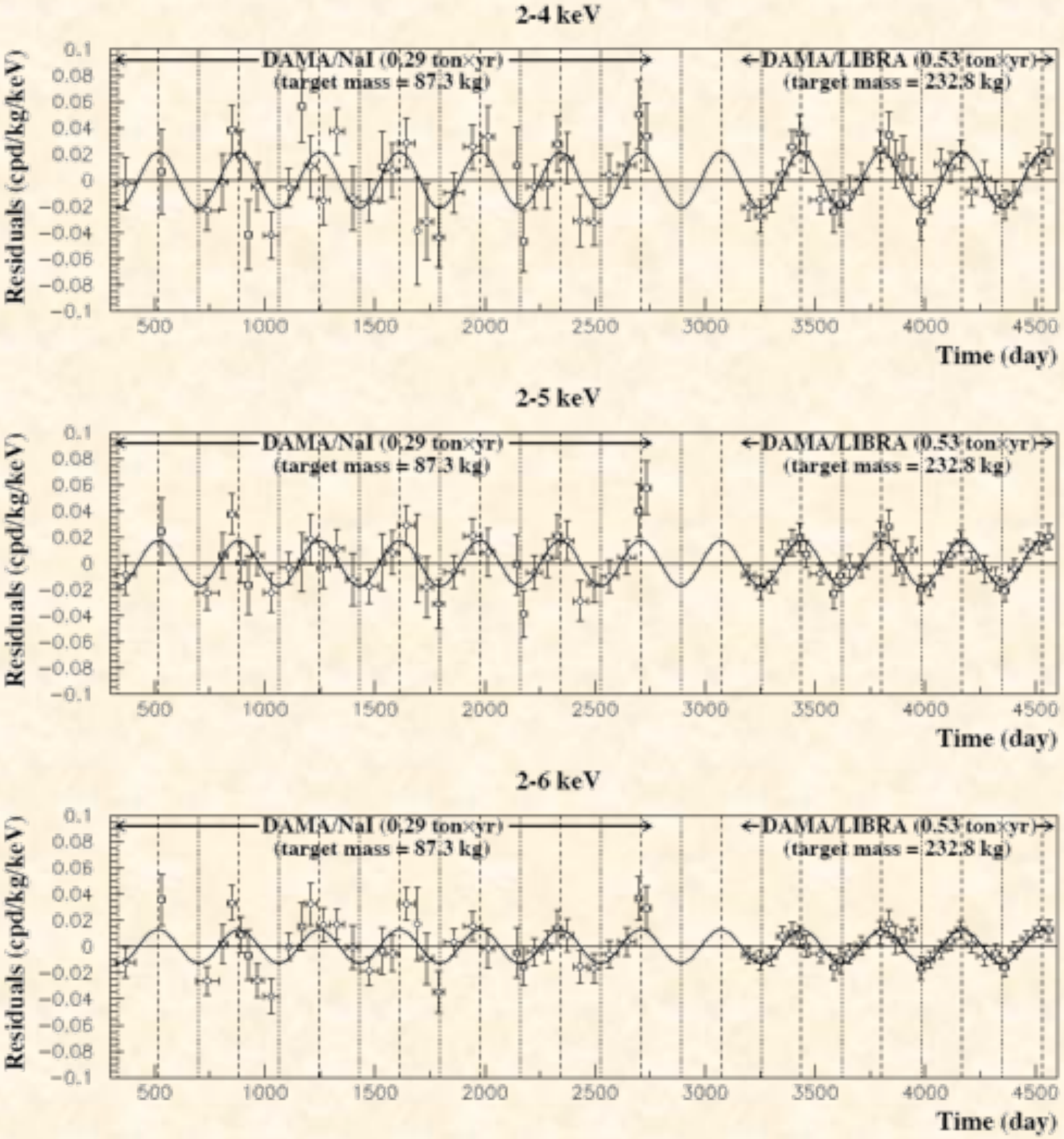
DAMA annual modulation

Effect at 8.2 σ C.L.

Single-hit events in the signal energy-window

Stability parameters do not modulate

Compatible to DM scatter
- off nuclei
- on electrons



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

DAMA annual modulation

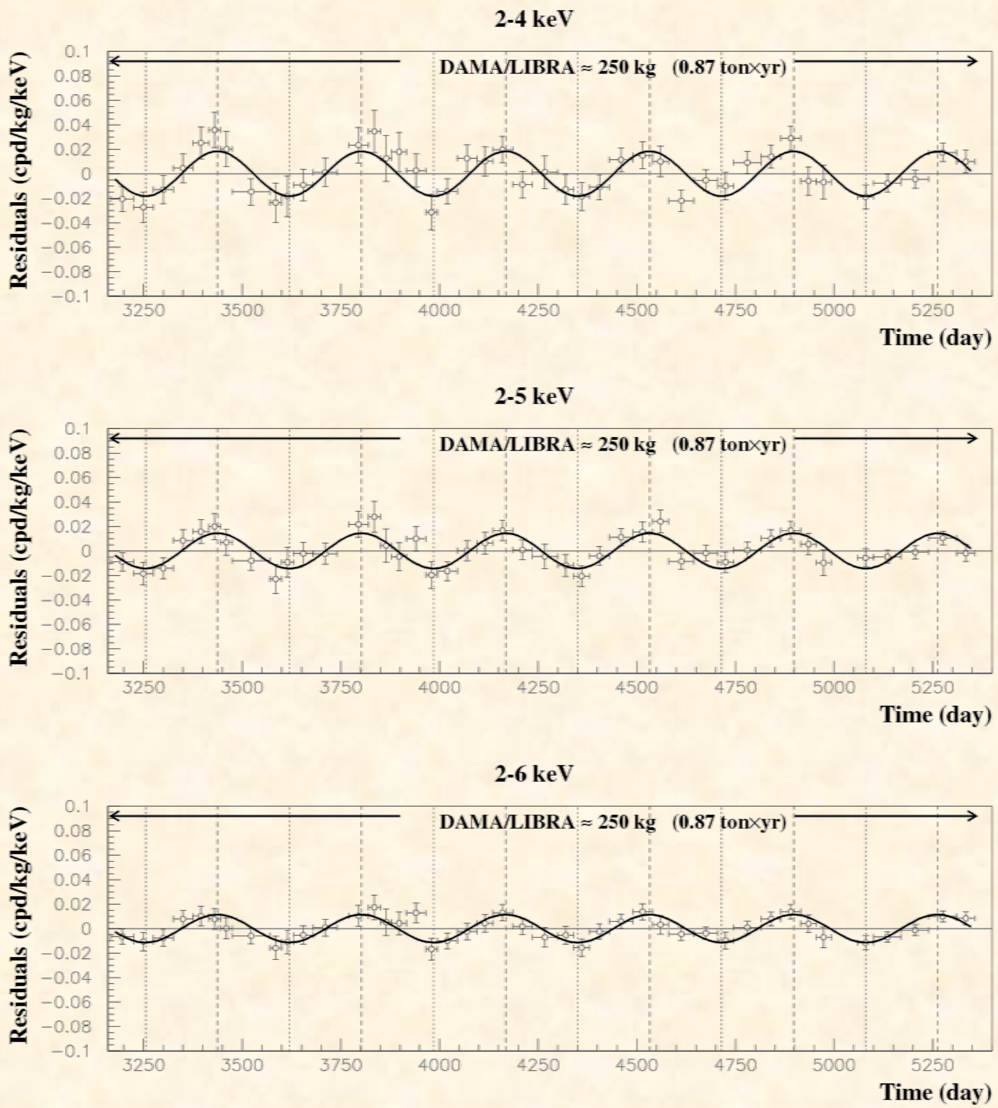
Effect at 8.9 σ C.L.

Cumulative exposure: 1.17 ton x yr (13 annual cycles)

S_m[2-6 KeV] = (0.0116 ± 0.0013) cpd/kg/keV

Phase = (146 ± 7) days

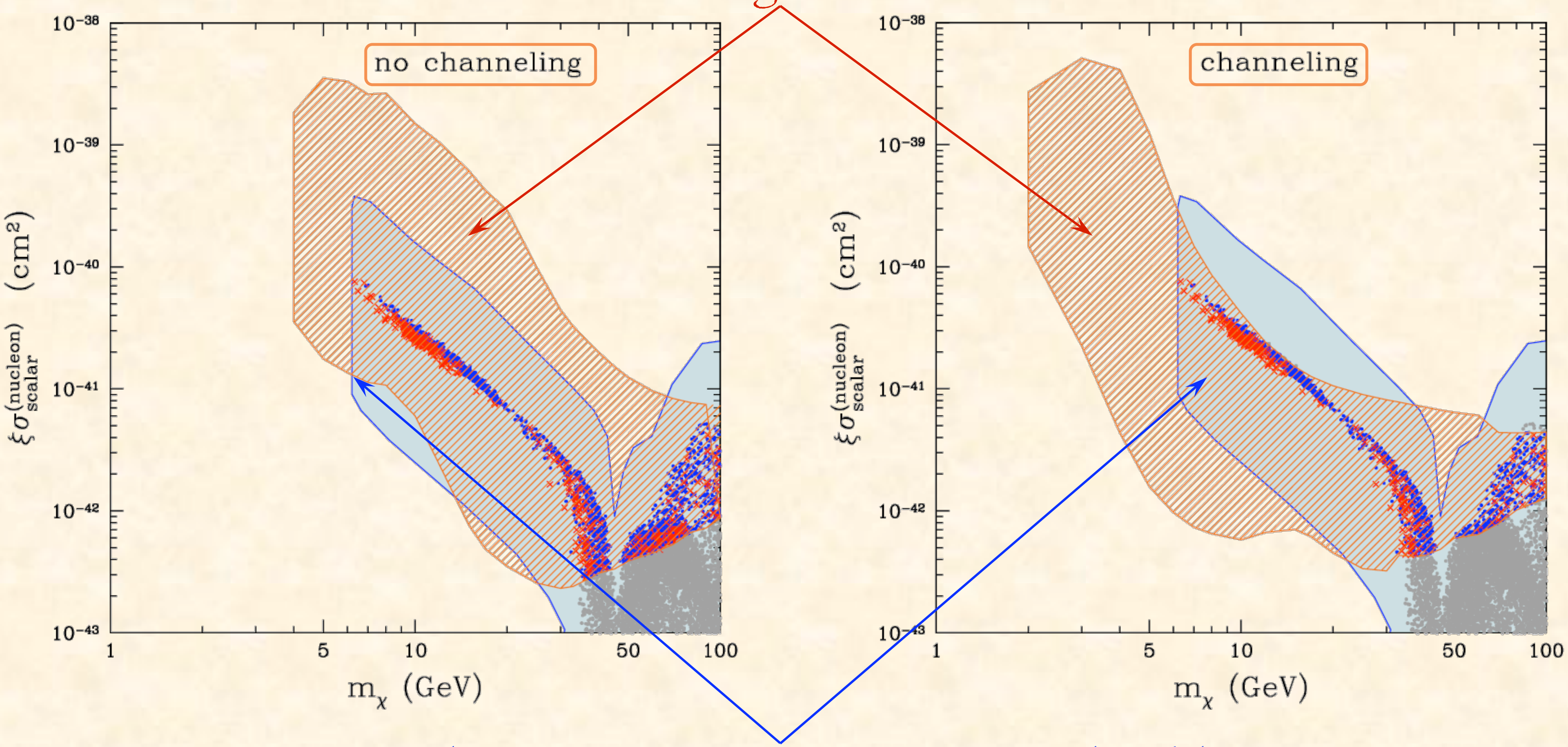
Period = (0.999 ± 0.002) years



R. Bernabei et al. (DAMA Collab.), arXiv:1002.1028 [astro-ph.GA]

DAMA annual modulation region

DAMA/LIBRA allowed region
(convolution over galactic halo models)

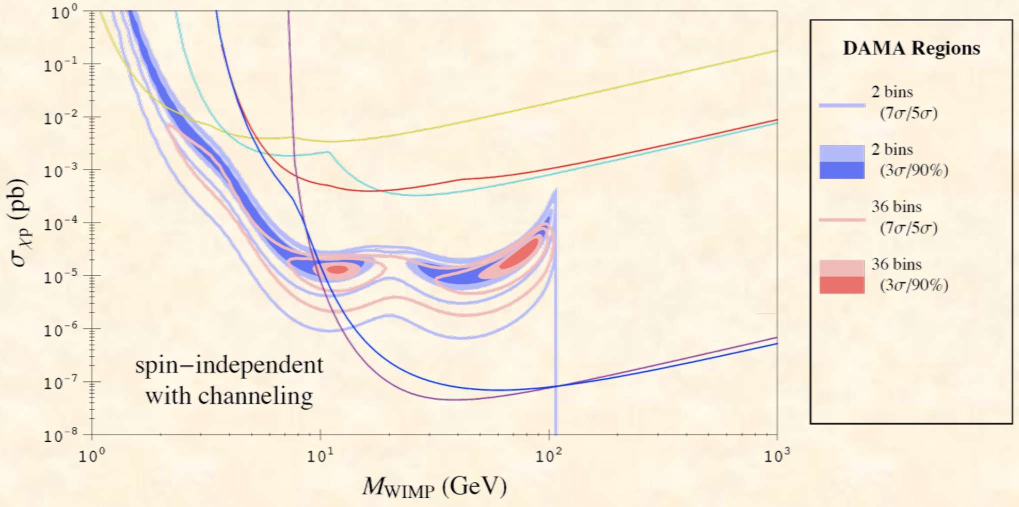


Neutralino DM: MSSM + gaugino non universal models
(includes hadronic uncertainites)

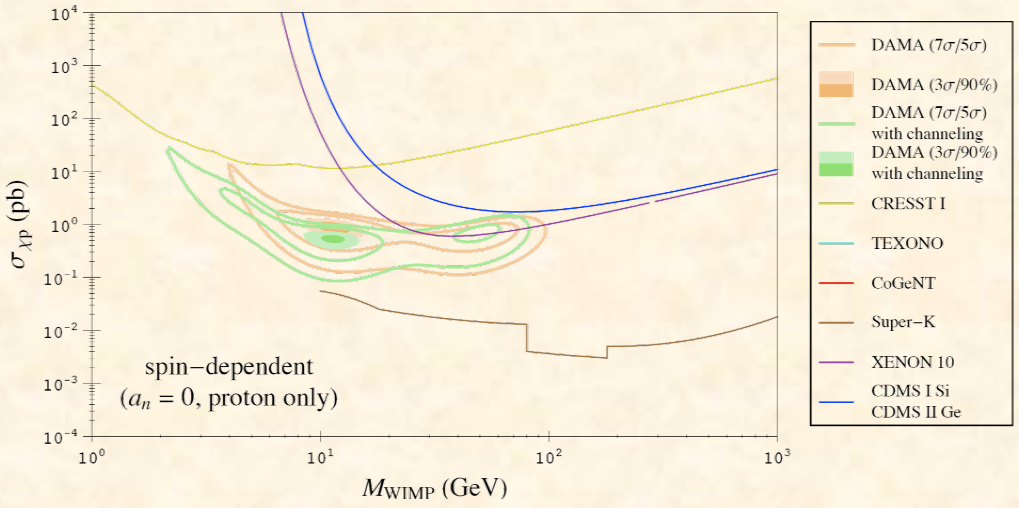
A. Bottino, F. Donato, N. Fornengo, S. Scopel, PRD 78 (2008) 083520

Light WIMP

Spin independent

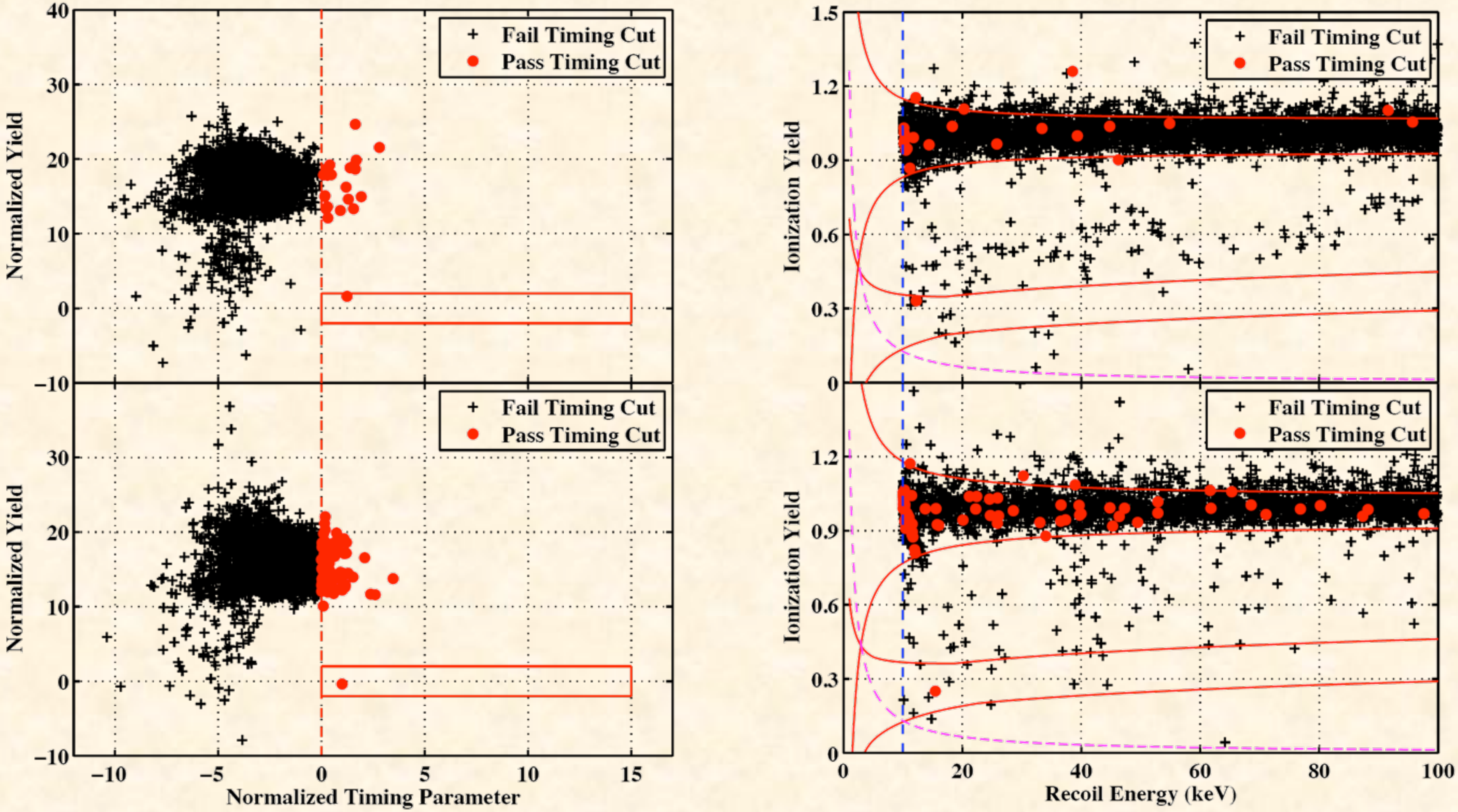


Spin dependent



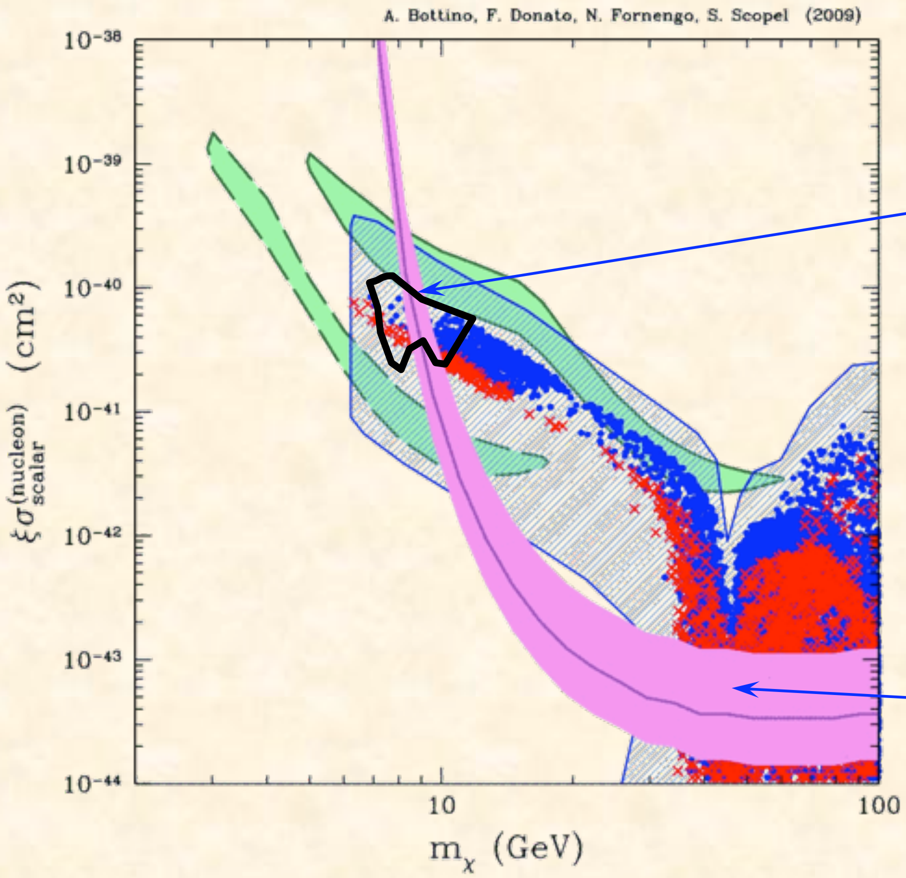
Savage, Gelmini, Gondolo, Freeze, JCAP 0904:010 (2009)

CDMS II – Final exposure (2009): 2 events pass cuts



Z. Ahmed (CDMS Collab.), arXiv:0912.3592 [astro-ph.CO]

Light DM and neutralinos



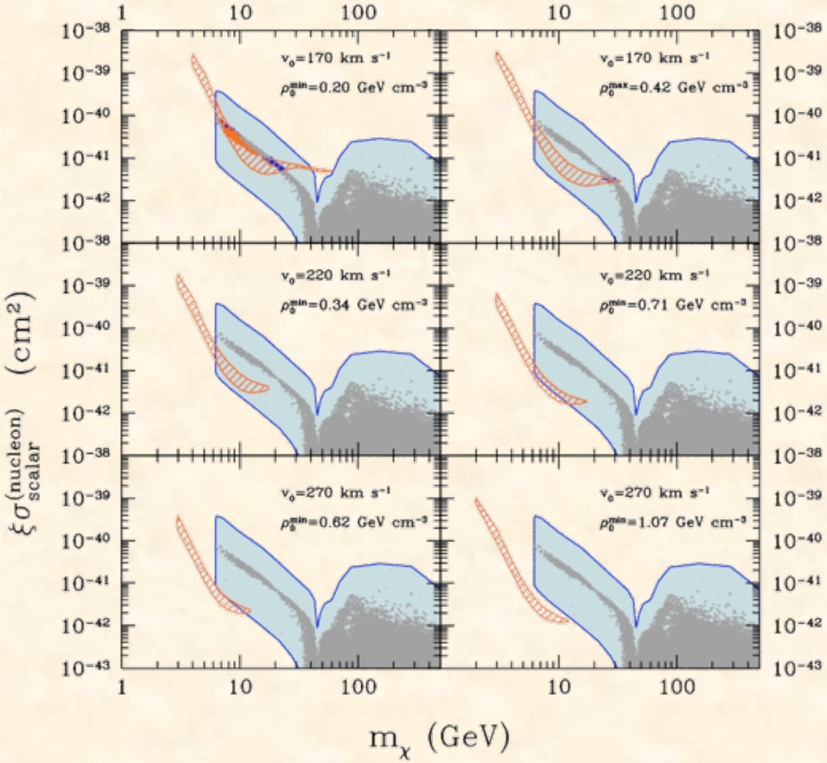
CoGeNT 2010: irreducible excess of bulk-like events below 3 KeV

Aalseth et al (CoGeNT), arXiv:1002.4703 [astro-ph.CO]

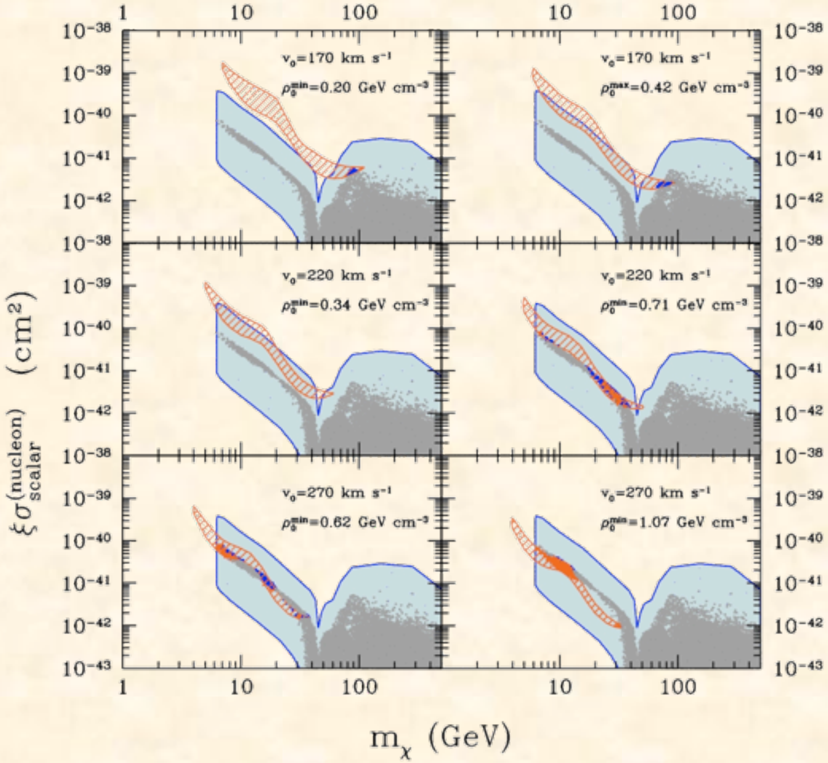
CDMS 2009 2 events If interpreted as DM

A. Bottino, F. Donato, N. Fornengo, S. Scopel, arXiv:0912.4025 [hep-ph]

Galactic halo modelling



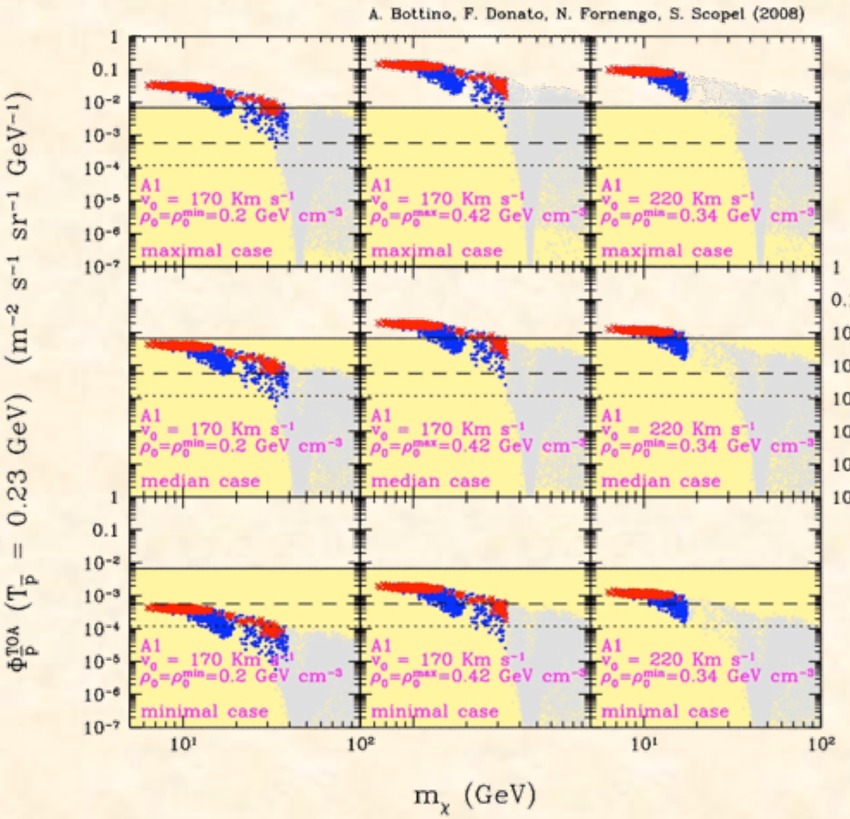
channeling



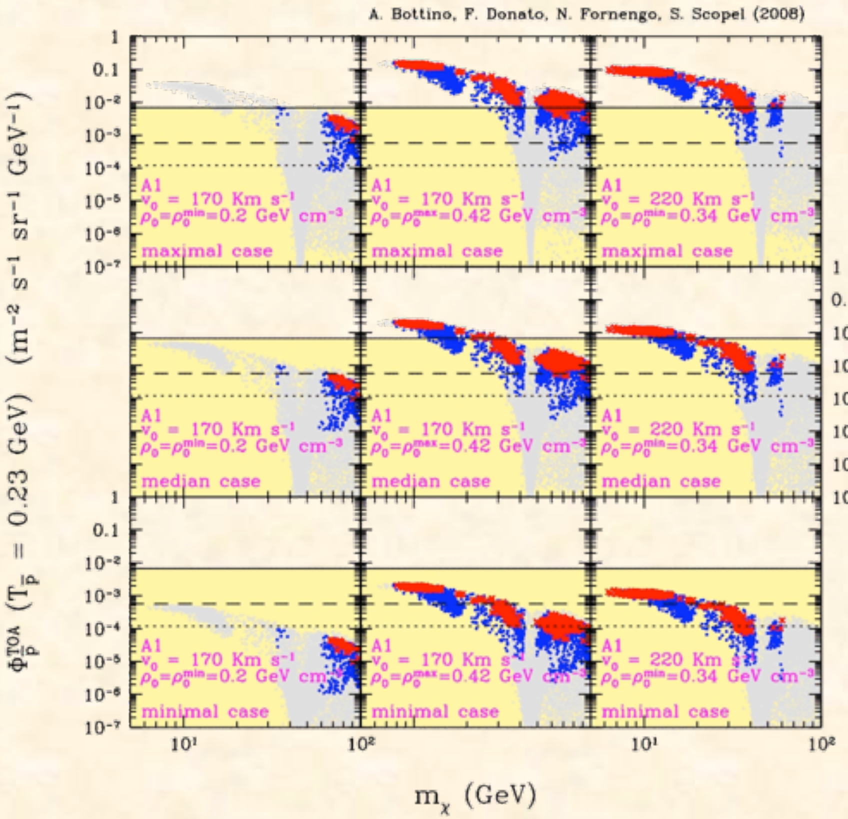
no channeling

A. Bottino, F. Donato, N.Fornengo, S. Scopel, PRD 78 (2008) 083520

Signal correlations: antiprotons in CRs



channeling



no channeling

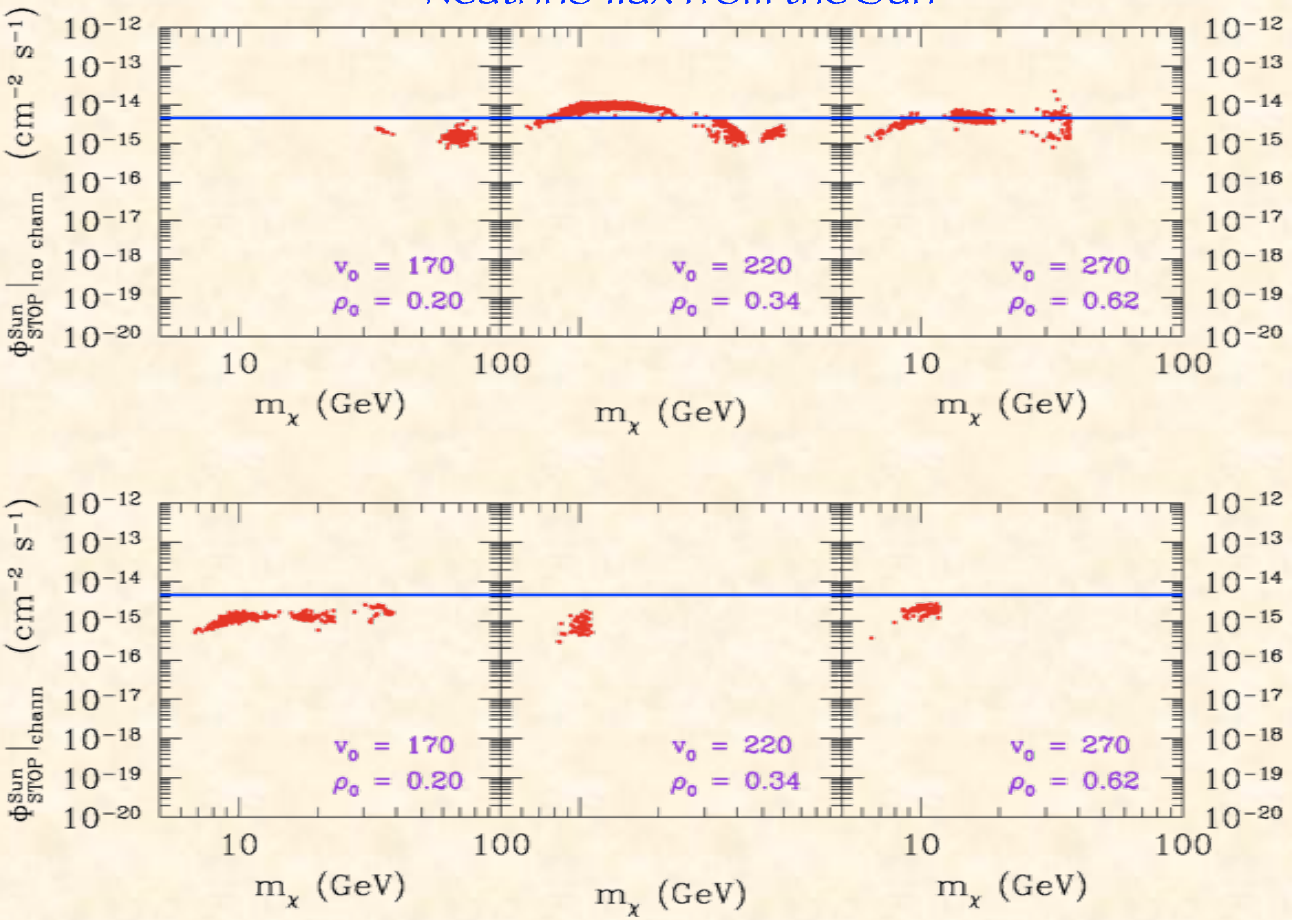
A. Bottino, F. Donato, N.Fornengo, S. Scopel, PRD 78 (2008) 083520

Signal correlations: neutrino telescopes

Neutrino flux from the Sun

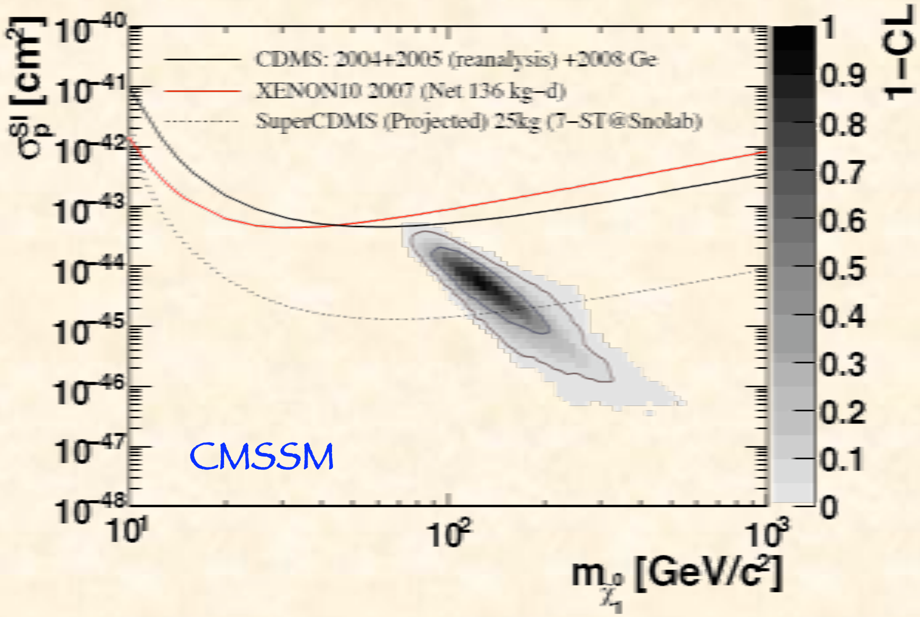
channeling

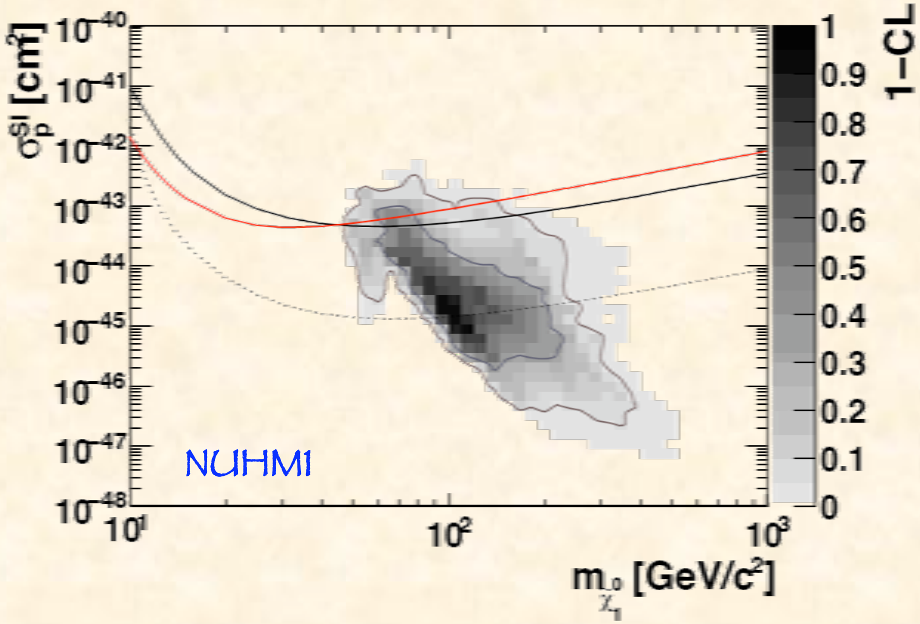
no channeling



V. Niro, A. Bottino, N.Fornengo, S. Scopel, PRD80 (2009) 095019

Minimal (and non-minimal) Supergravity

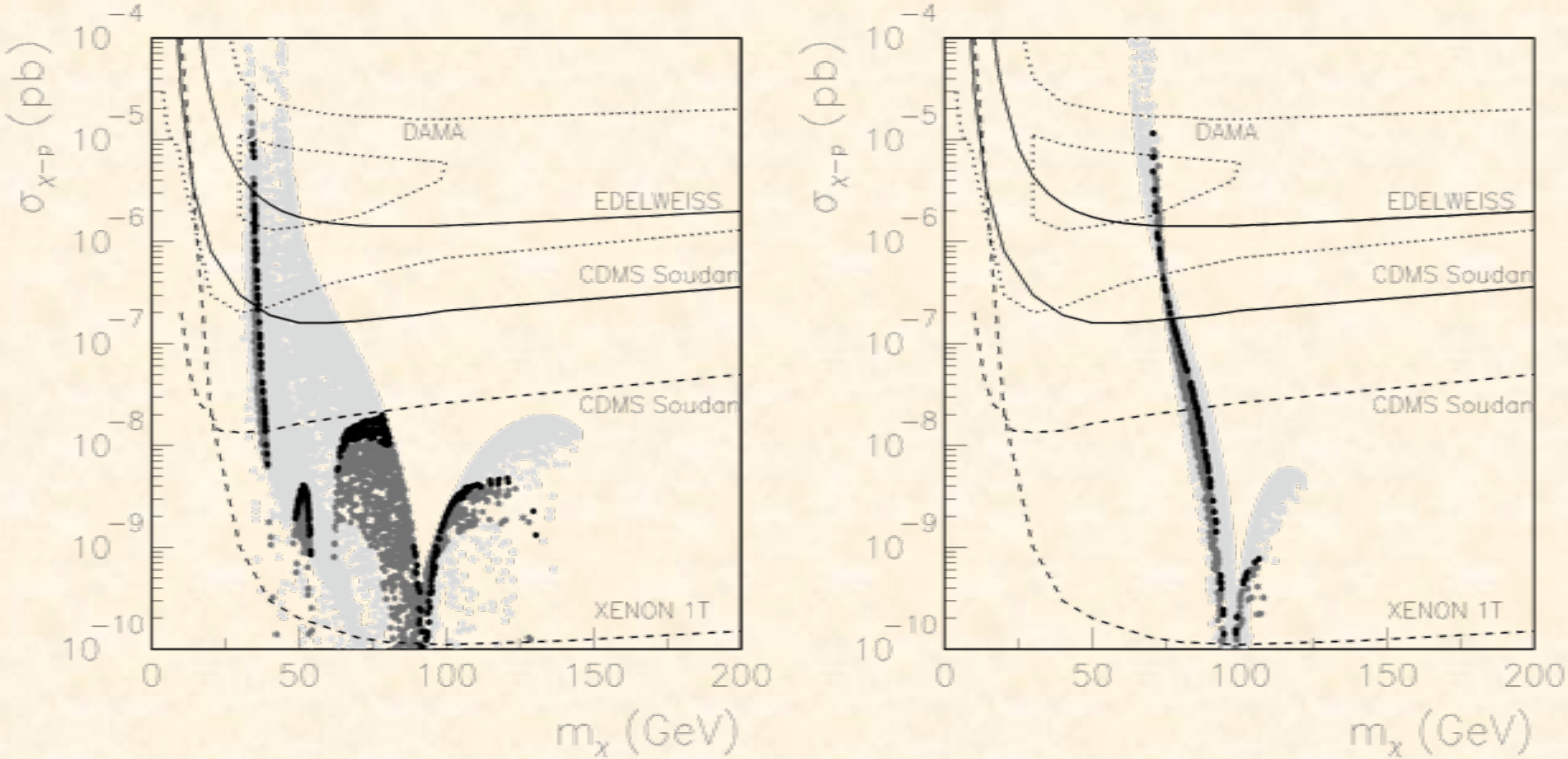




Buchmueller et al., Eur.Phys.J.C64:391-415,2009

Neutralinos in the NMSSM

NMSSM = MSSM + singlet superfield
Addresses naturally the mu-problem
Higgs and neutralinos may be light

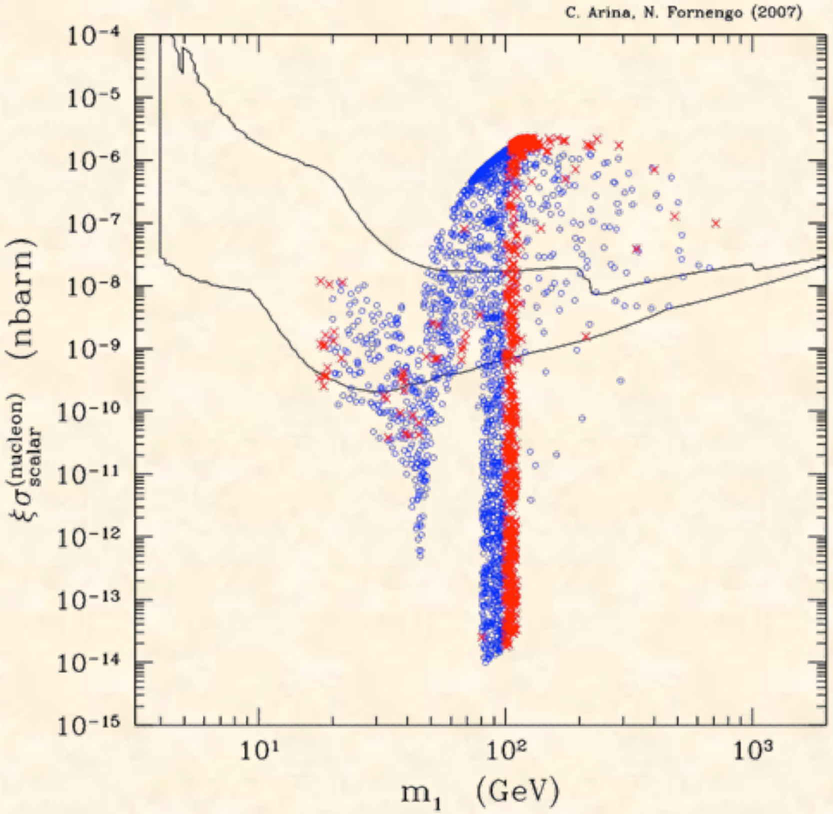


Cerdeno, Gabrielli, Lopez-Fogliani, Munoz, Teixeira, JCAP0706:008,2007

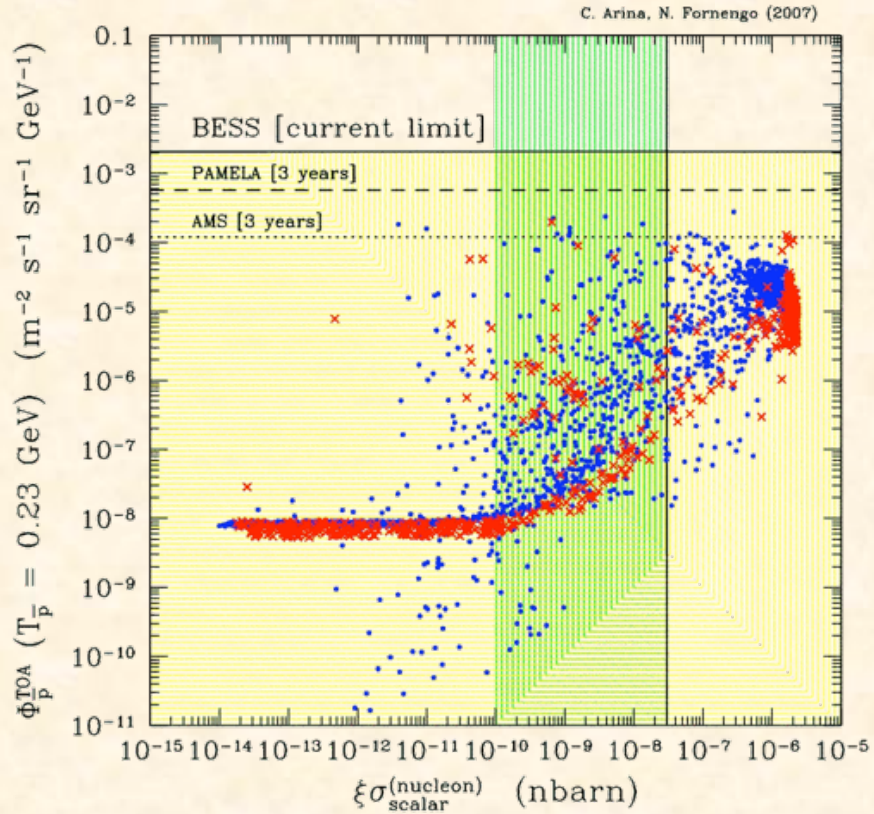
Sneutrinos in Left-Right models

MSSM + right-handed neutrino superfields

Addresses DM + neutrino mass in the same sector



Direct Detection



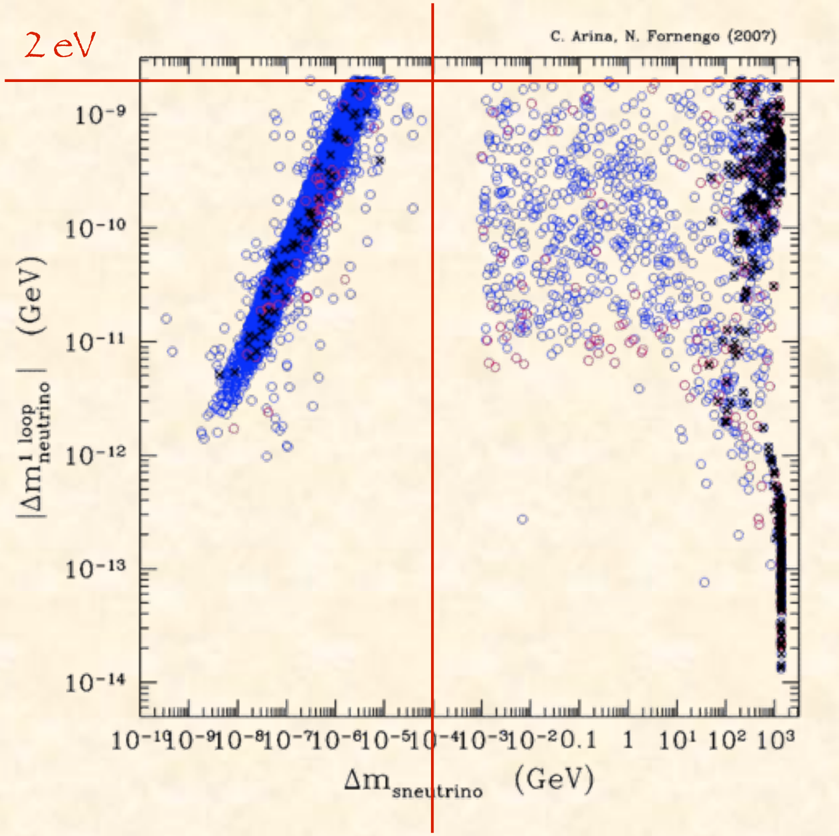
Antiprotons vs. Direct Detection

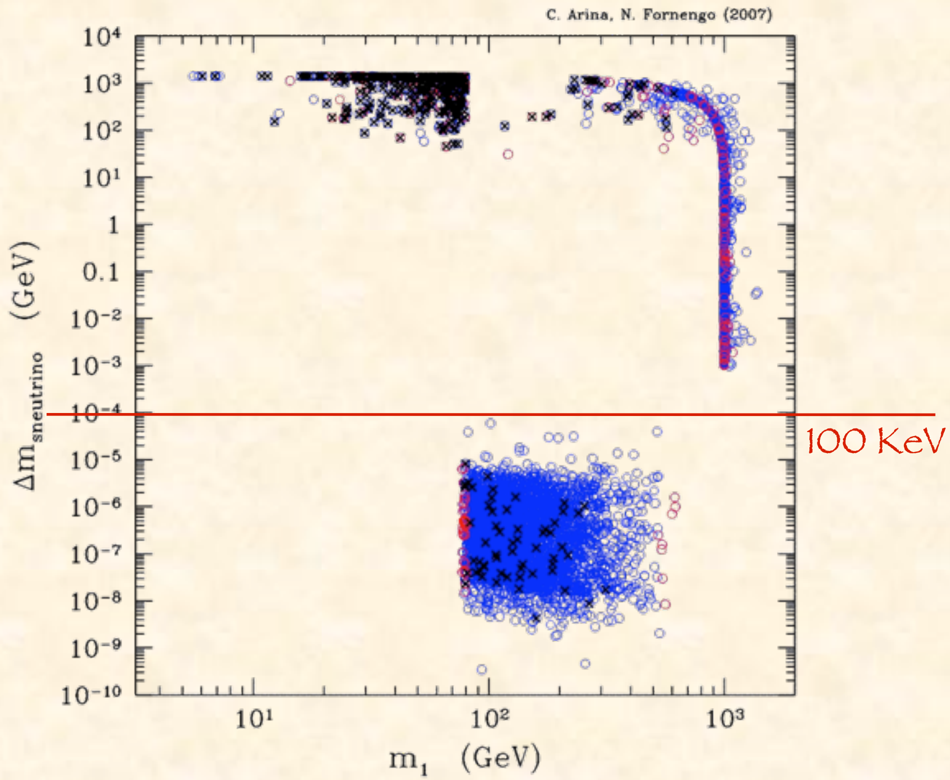
C. Arina, N. Fornengo, JHEP 0711 (2007) 029

Sneutrinos as non-elastic dark matter

MSSM + right-handed neutrino superfields + L-violating terms

Sneutrino coupling to Z: (Z snu_1 snu_2) ⟶ inelastic



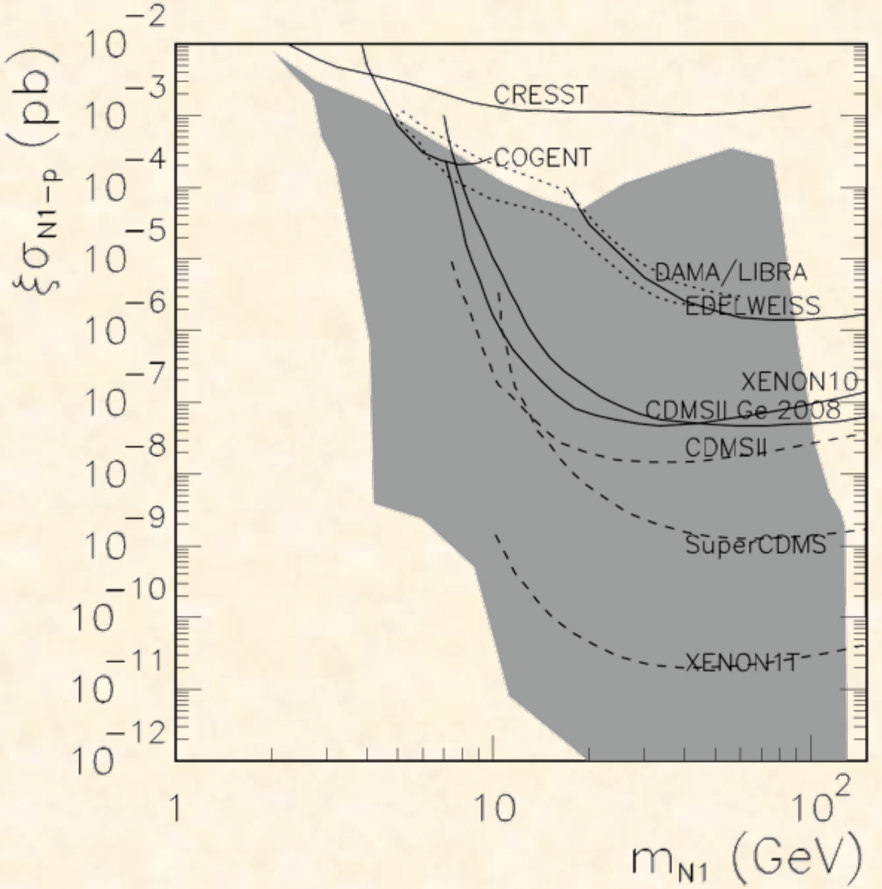


C. Arina, N. Fornengo, JHEP 0711 (2007) 029

Sneutrinos in the NMSSM

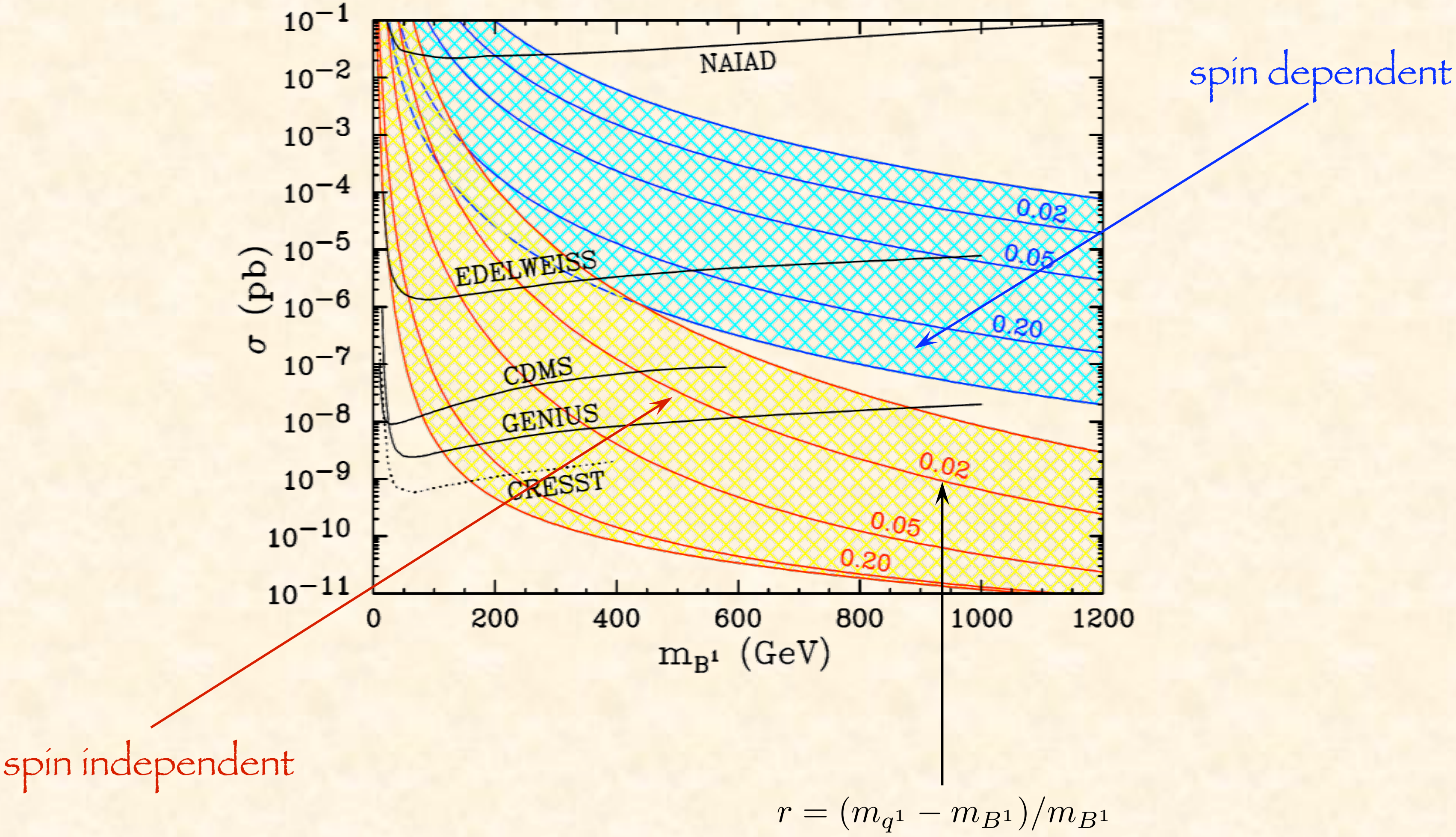
NMSSM + right-handed neutrino superfield

Addresses DM + neutrino mass + mu-problem



Cerdeno, Seto, JCAP 0908 (2009) 032

Universal extra-dimension theories



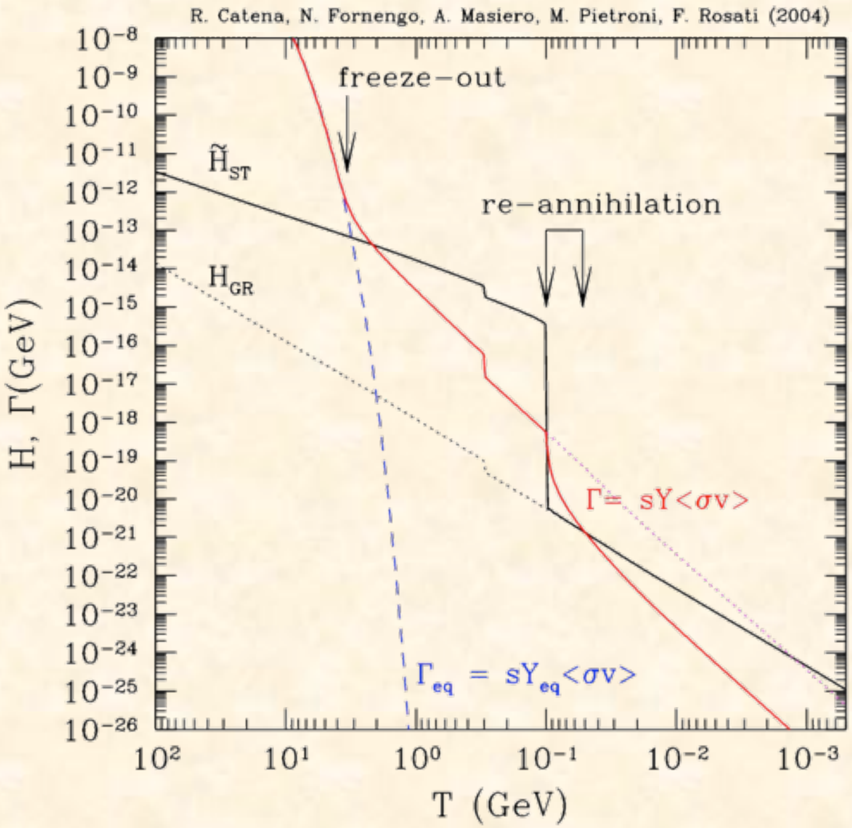
Cheng, Feng, Matchev, PRL 89 (2002) 211301

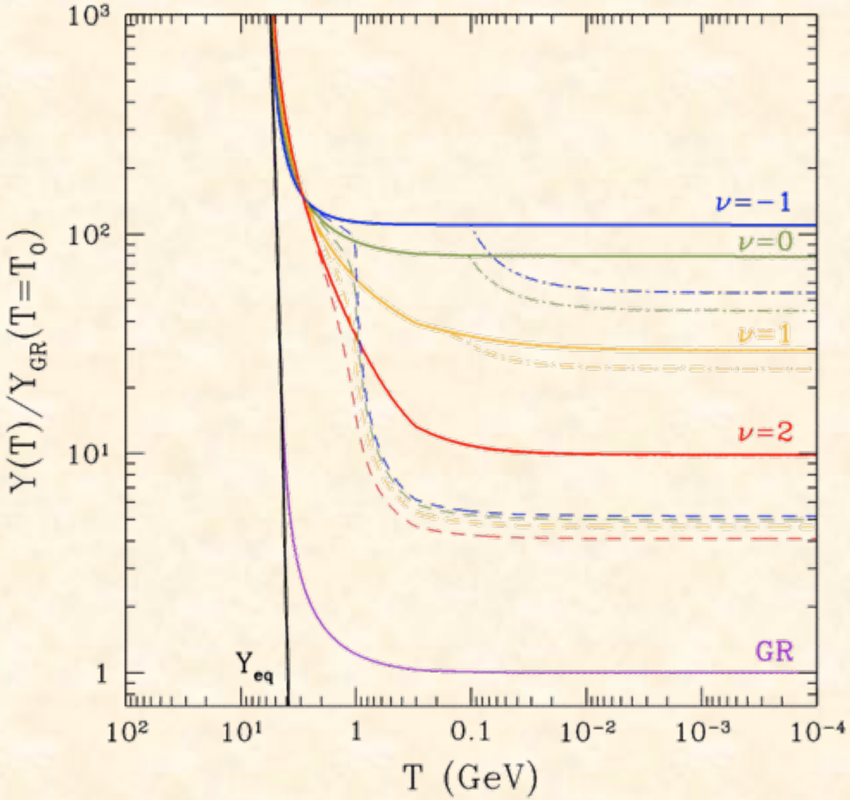
Back to Cosmology

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

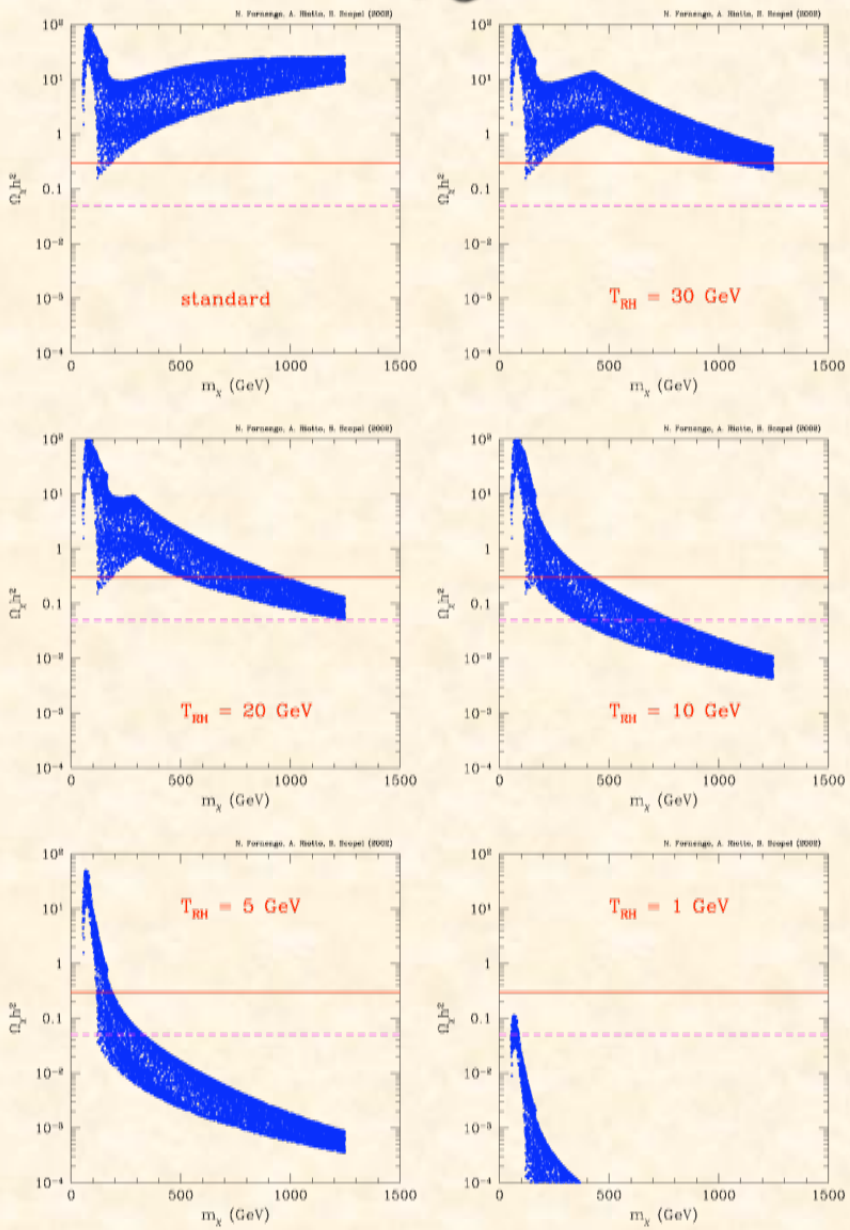


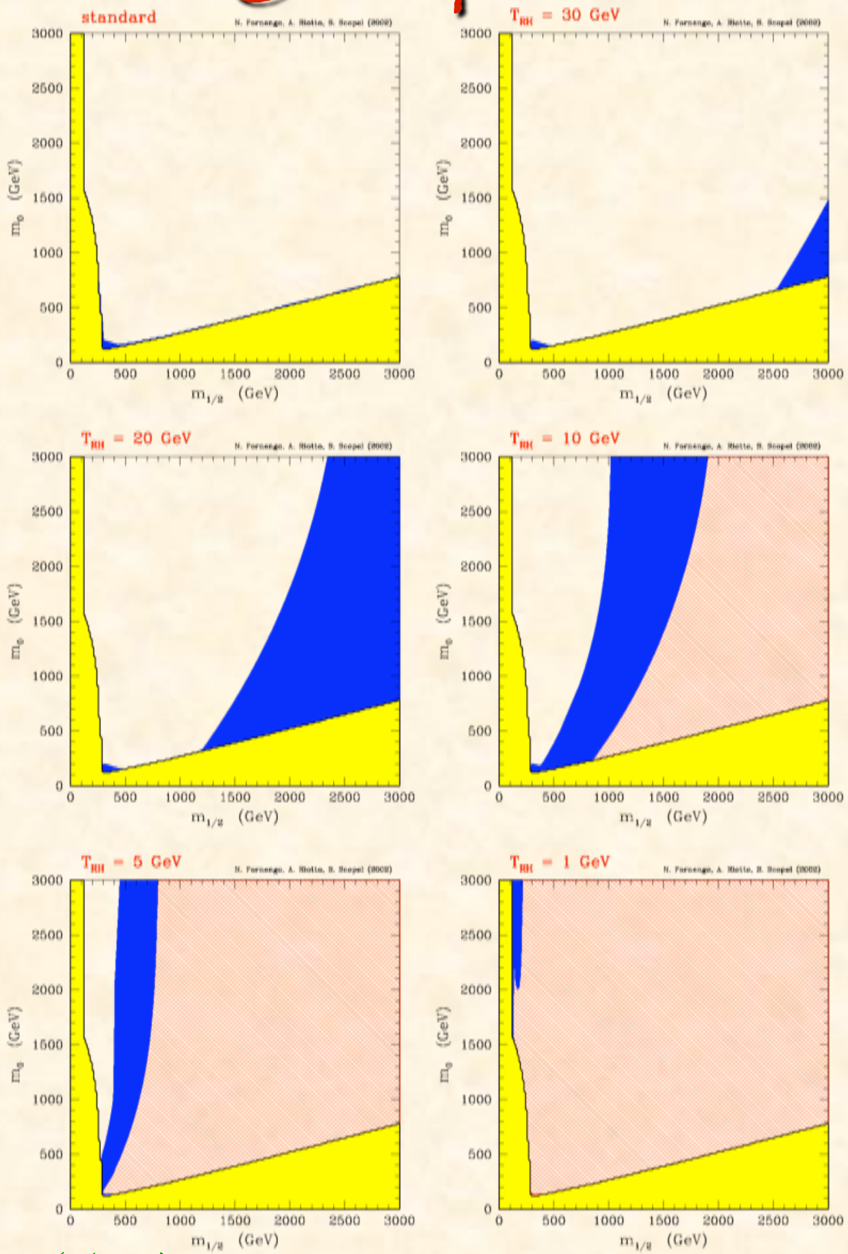


$$H(T) = A(T)H_{\rm GR}(T)$$

$$A(T) = 1 + \eta \left(\frac{T}{T_{\rm f}}\right)^{\nu} \tanh\left(\frac{T - T_{\rm re}}{T_{\rm re}}\right)$$

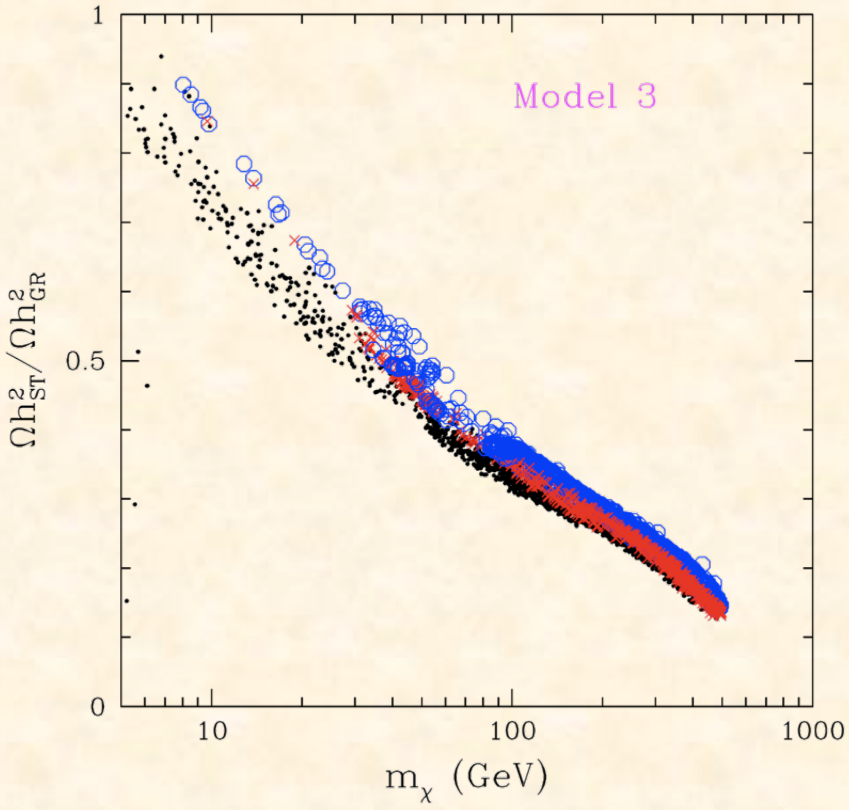
Cosmology with a low-reheating temperature

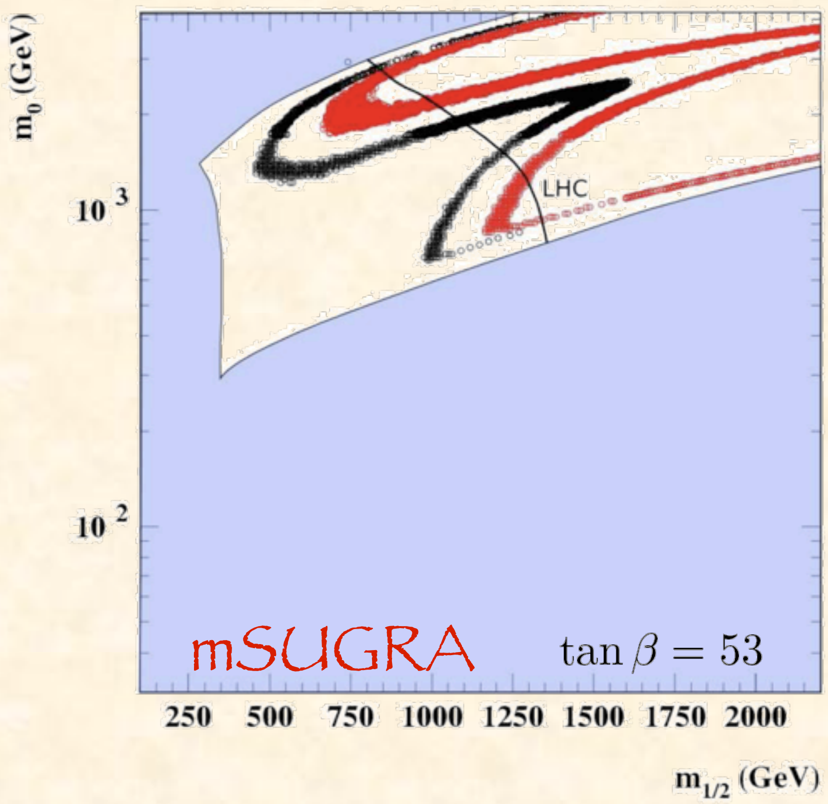




N. Fornengo, A. Riotto, S. Scopel, PRD 67 (2003) 023514

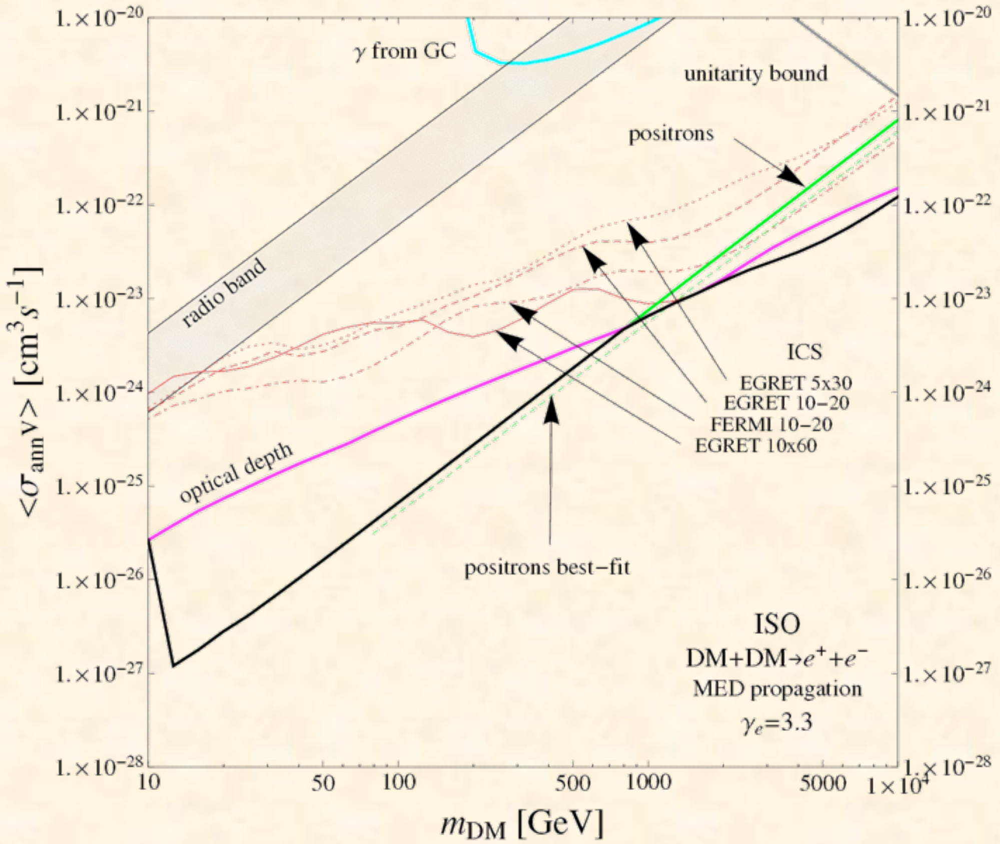
Scalar-tensor gravity with 2 scalar fields

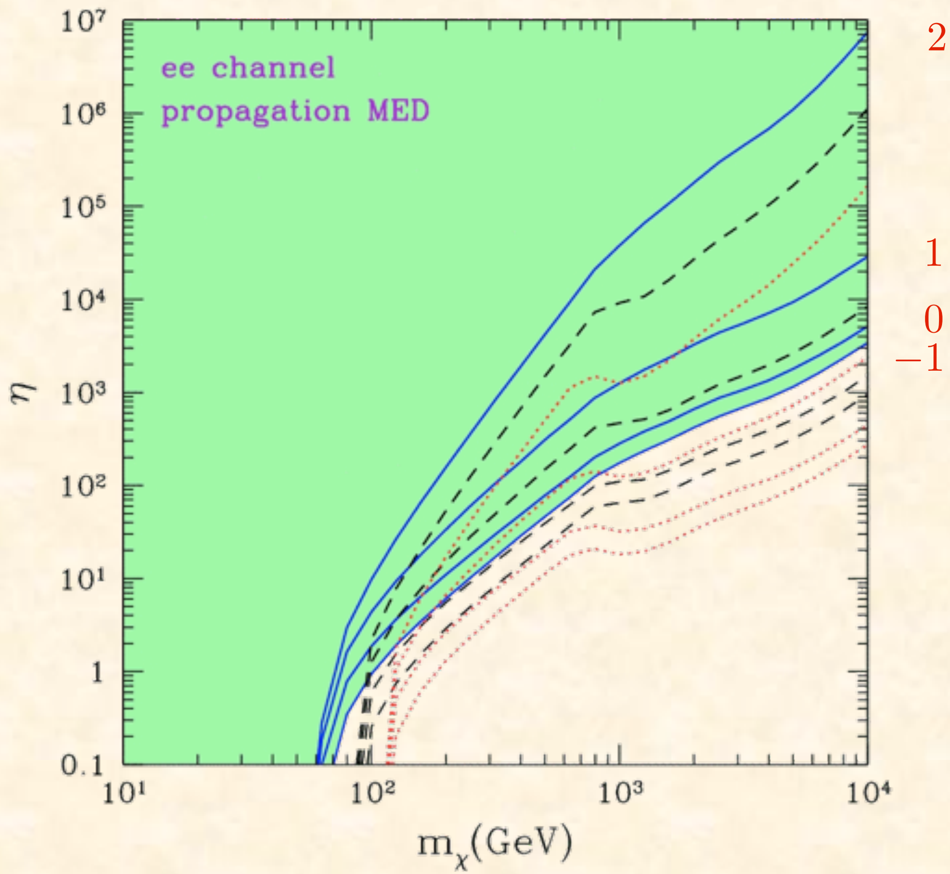




R. Catena, N. Fornengo, A. Masiero, M. Pietroni, M. Schelke, JHEP 0810 (2008) 003

Astrophysical bounds on pre-BBN Cosmology





$$H(T) = A(T) H_{\rm GR}(T)$$

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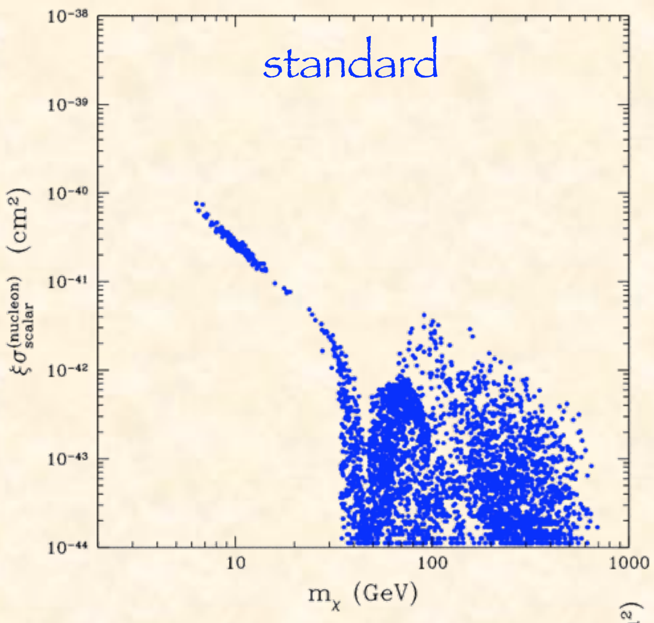
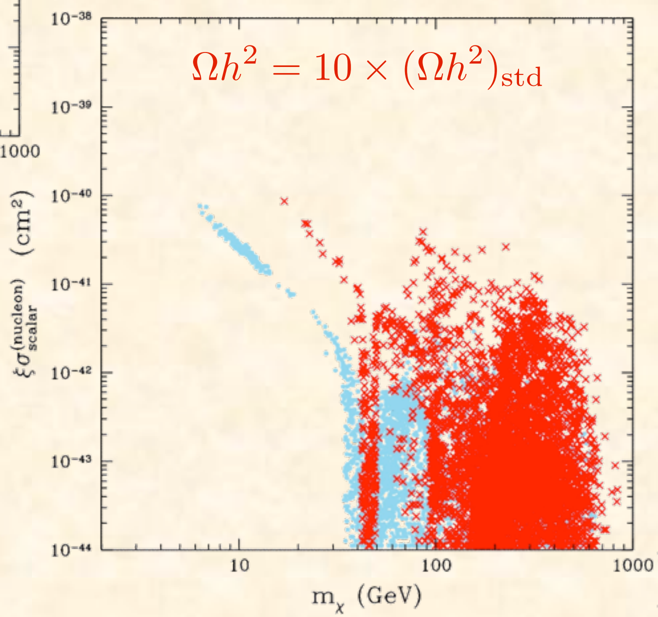
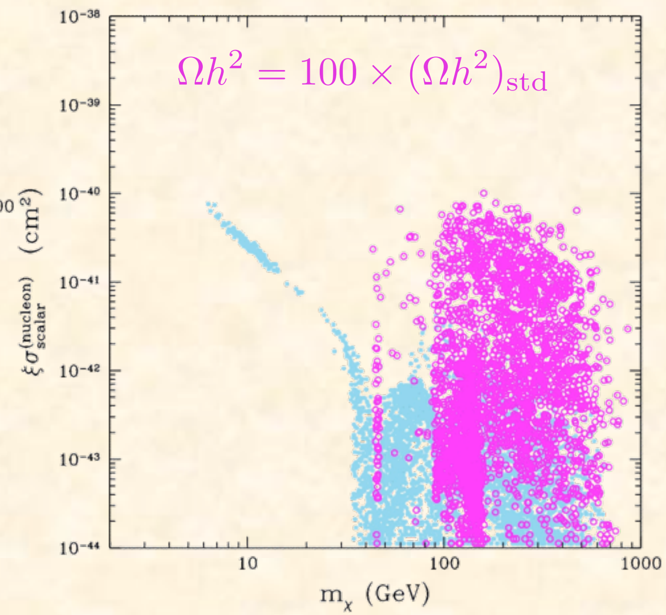
R. Catena, N.Fornengo, M. Pato, L. Pieri, A. Masiero, arXiv:0912.4421 astro-ph.CO]

Effect of modified Cosmology







Conclusions

- Astropysical searches may be proficiently 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 (and to some extent of the underlying New Physics model)

- Different detection signals probe different properties of the DM particle and feel different features of the galactic environment

- DM searches requires:
  - To exploit specific and typical signatures of the various types of signals
  - Better knowledge of the astrophysical environment

Conclusions

- Cosmological properties and astrophysical signals of particle DM candidates can either guide or complement accelerator physics searches
- Viceversa, accelerators, with their capability of identifying (at least part of the) BSM particles and their properties, will allow to shape out the predictions for DM signals
- The two approaches are therefore both fundamental in the study of the DM hypothesis
  - Accelerators: prove the existence of Physics BSM and directly discover the new physical states
  - DM searches: prove that the new physical states explain the DM puzzle and explicitely dentify the DM presence in the astrophysical environment
- The interplay between the two approaches may also tell something on the cosmological evolution of the early Universe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