The "Torino code" NUMERICAL TOOLS FOR PARTICLE DARK MATTER

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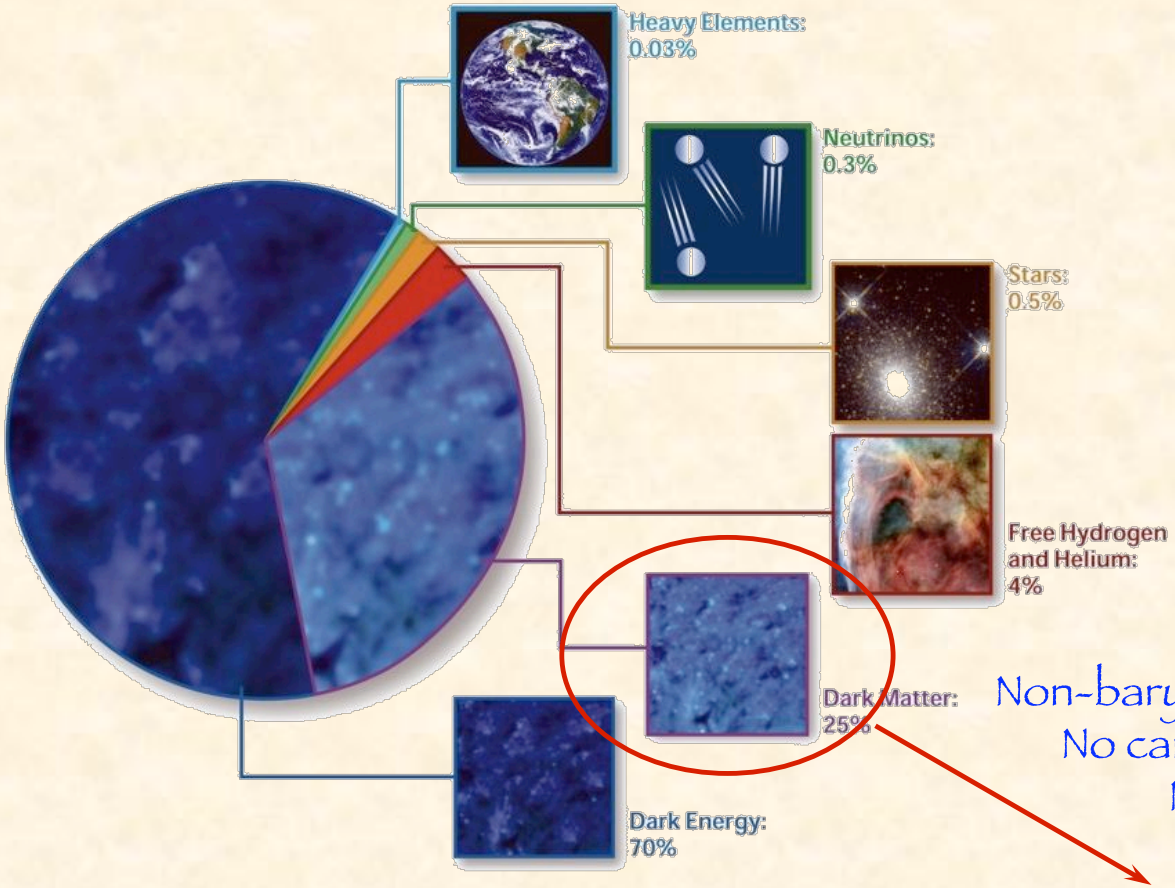
INFN Torino

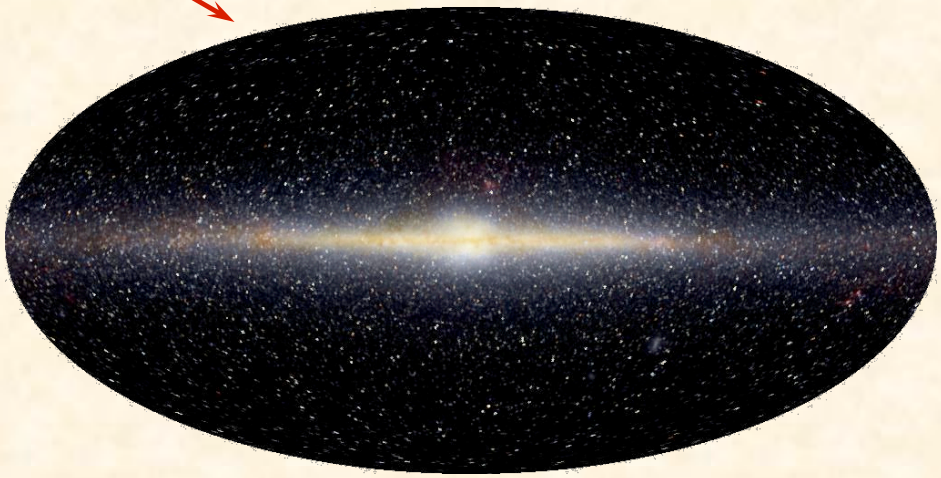
LC09: e+e- Physics at the TeV scale and the Dark Matter Connection

Perugia – 22.09.2009

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

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)

The Particle Dark Matter tool

- Particle candidate
  - Definition of the BSM model and identification of the DM candidate
  - Determination of the full spectrum and couplings
- Cosmology of the particle candidate
  - Definition of the cosmological model: H(T)
  - Calculation of the (co)annihilation cross section $< \sigma v >$
  - Solution of the Boltzmann equation: relic abundance Ωh^2
- Astrophysical signals of the DM particle
  - Modelization of the galactic halo
  - Direct detection cross section and recoil spectrum
  - Calculation of the source spectra for indirect detection:
    - Neutrinos, gamma-rays, positrons, antiprotons, antideuterons
  - Transport of the spectra: signal fluxes

The "Torino Code" for Particle Dark Matter

N. Fornengo, A. Bottino, S. Scopel, F. Donato
R. Lineros, C. Arina, V. Niro

- FORTRAN numerical code for particle DM calculations

- Dates back to 1990, and it has been progressively improved to become a self-consisent tool for neutralino dark matter calculations

- 1990-1994: N. Fornengo, A. Bottino, G. Mignola, M. Pignone
  - MSSM
  - Neutralino relic abundance
  - Neutrino signal from Earth and Sun
- 1991-1994: N. Fornengo, S. Scopel, A. Bottino
  - Minimal and non-minimal SUGRA
  - Direct detection
- 1995, 1998, 2000, 2008: N. Fornengo, F. Donato
  - Antiprotons, antideuterons
- 2000, 2004: N. Fornengo, S. Scopel
  - Galactic halo modeling
  - Gamma-rays
- 2003: N. Fornengo, A. Bottino. S. Scopel
  - Gaugino non-universal MSSM
- 2004: N. Fornengo
  - Alternative cosmologies
- 2008, 2009: N. Fornengo, R. Lineros, F. Donato
  - Positrons, electrons
- 2005, 2008: N. Fornengo, V. Niro
  - Neutrino oscillation on the neutrino signal

- 2007: N. Fornengo, C. Arina
  - Sneutrino DM: relic abundance and detection rates
  - Relic abundance: towards a generic candidate

Particle Physics Model

Dark Matter Code

- Relic abundance
- Galactic model
- Direct Detection Signal
- Indirect Detection Signals
- Spectra generator
- Transport

The Particle Physics Model

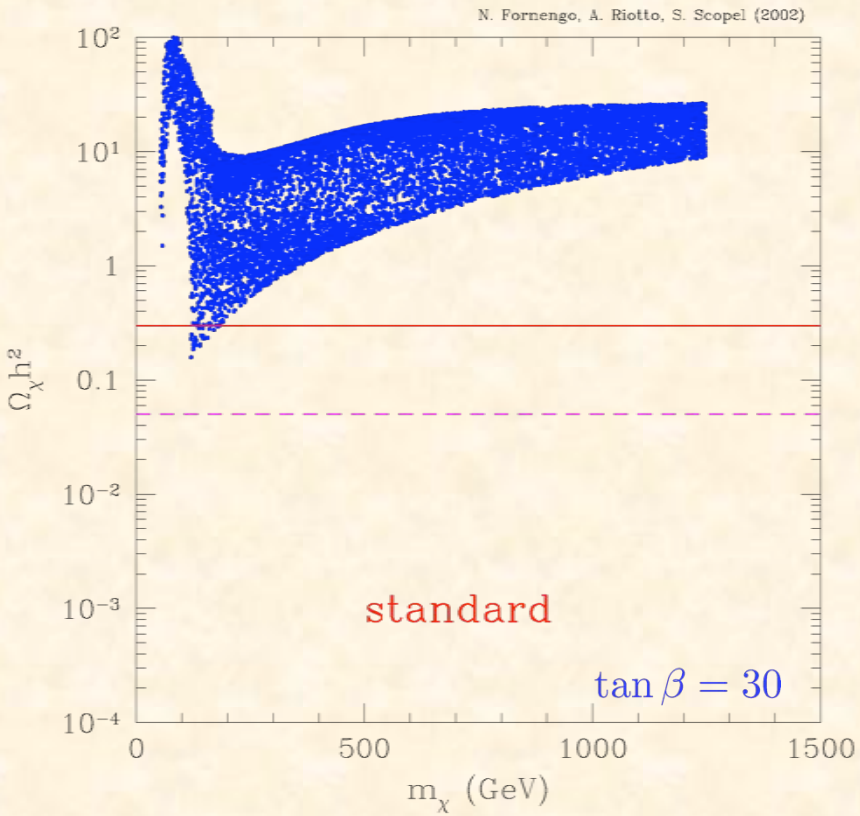
- Neutralino DM
  - Low-energy MSSM
  - Minimal SUGRA
  - SUGRA with non-universal scalar masses in the Higgs sector
  - Low-energy MSSM with non-universal gaugino masses (light neutralinos)
- Sneutrino DM
  - LR models
  - Majorana mass models
  - See-saw models

- Experimental bounds on Higgs searches
- Experimental bounds on SUSY searches
- Muon anomalous magnetic moment
- B rare decays

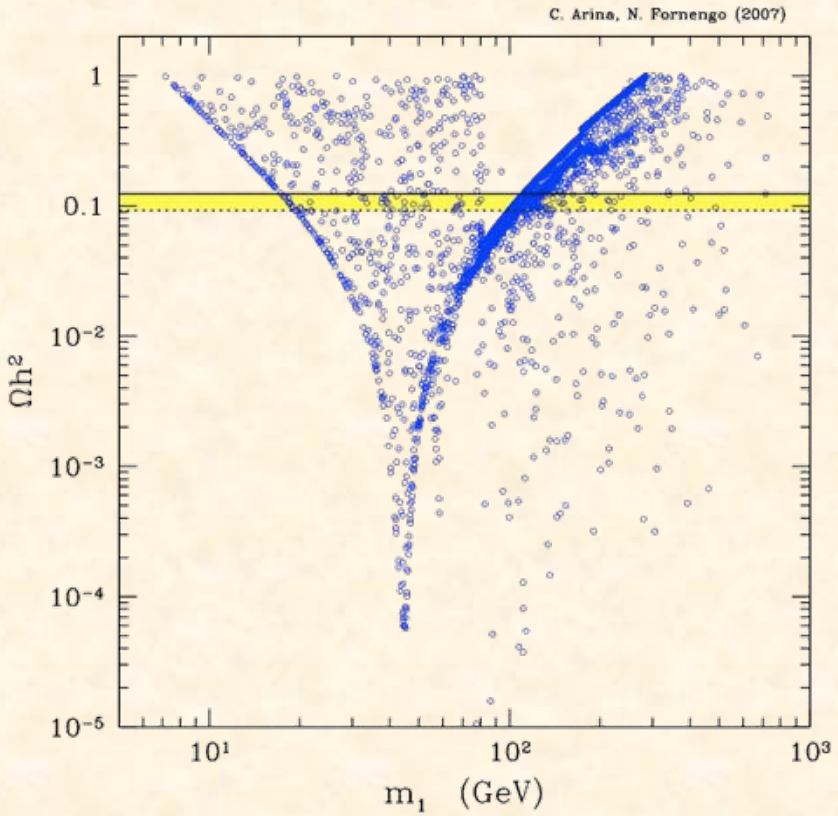
DM Code: Relic Abundance

- Thermally avraged annihilation cross section
  - Full set of diagrams and channels (neutralino; sneutrino)
- Cosmological model
  - Standard cosmology
  - Low-reheating cosmology
  - Alternative cosmologies (scalar-tensor, kination, D-brane)
- Solution of the Boltzmann equation
  - Approximate analytic (when appropriate; fast)
  - Numerical

Relic abundance



Neutralino
mSUGRA



Sneutrino
Left-right models

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

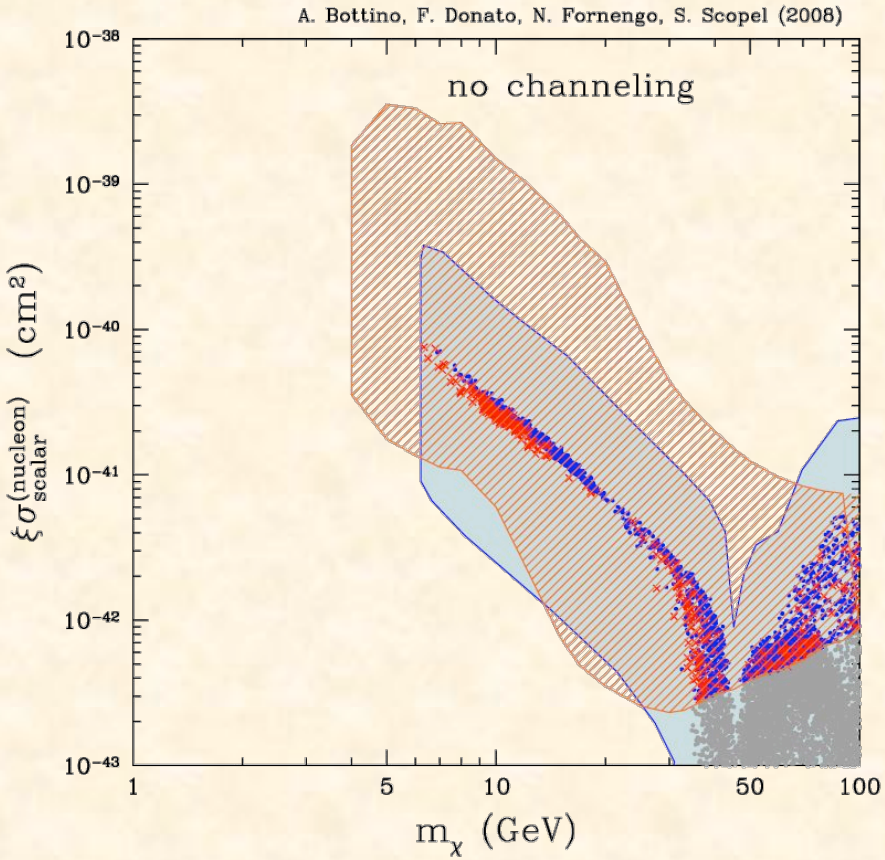
DM Code: Galactic Halo Model

- Analytic models
  - Isothermal sphere
  - Axisymmetric and triaxial models
  - Models from numerical simulation (NFW, Moore, Einasto)
- Numerical models
  - Spherical models through Eddington theory (isotropic and non-isotropic)

DM Code: Direct Detection

- Coherent cross section
  - Full set of diagrams
  - Hadronic uncertainties
  - Helm form factor
- Spin-dependent cross section
  - Full set of diagrams
  - Spin form-factors from numerical studies
- Recoil spectra
  - For all galactic models
  - Experimental resolution may be included
  - Total rate and annual modulation effect

Direct detection



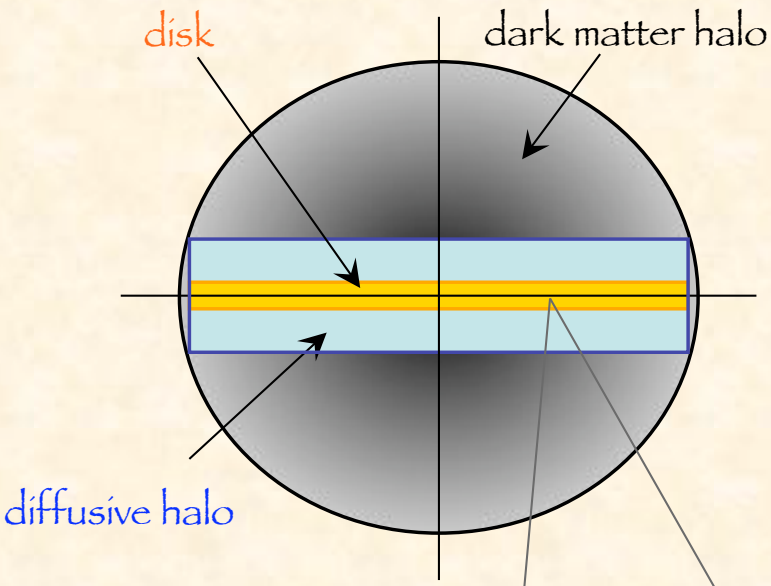
A. Bottino, F. Donato, N. Fornengo, S. Scopel, PRD 78 (2008) 083520

DM Code: Indirect Detection

- Galactic antiprotons, antideuterons, positrons, electrons
  - Source spectra modeled from PYTHIA (fitted; library)
  - Galactic transport in a 2-zone diffusion model (*) for various DM profiles
  - [Astrophysical backgrounds are also calculated]

(*) Galactic propagation: implements the results from the collaboration with P. Salati, D. Maurin, R. Taillet, T. Delahaye, J. Lavalle

Galactic antimatter



Secondaries

$$
\begin{aligned}
p_{\rm CR} + p_{\rm ISM} &\longrightarrow \bar{p}, \bar{D}, e^+ \\
p_{\rm CR} + {\rm He}_{\rm ISM} &\longrightarrow \bar{p}, \bar{D}, e^+ \\
{\rm He}_{\rm CR} + p_{\rm ISM} &\longrightarrow \bar{p}, \bar{D}, e^+
\end{aligned}
$$

Produced in the disk

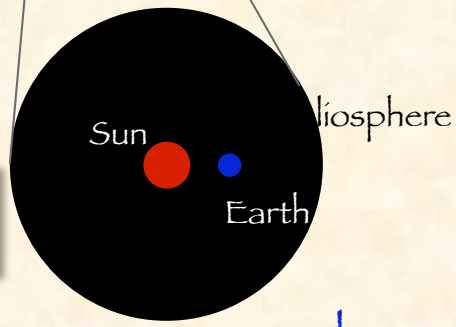
Propagation and energy redistribution in the diffusive halo

DM signal

$$\chi\chi \longrightarrow (...) \longrightarrow p\bar{p}, D\bar{D}, e^+e^-$$

Produced in the DM halo

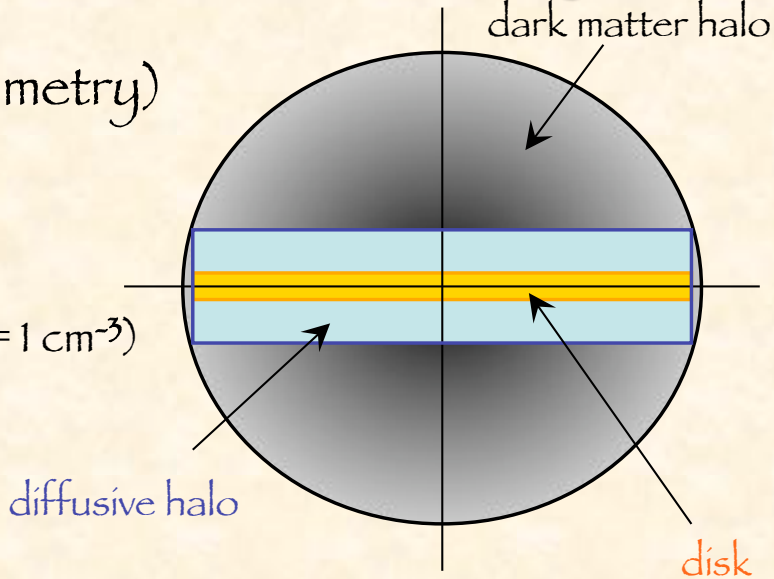
Propagation and energy redistribution in the diffusive halo



solar modulation

Diffusion and propagation in the Galaxy

- Two-zone diffusion model (cylindrical symmetry)
  - Thin disk
    - ✓ Radius R = 20 kpc
    - ✓ Thickness h = 100 pc
    - ✓ Surface density of IS gas: $\Sigma = 2hn_{ISM}$ ($n_{ISM} = 1\ cm^{-3}$)
  - Diffusive halo
    - ✓ Radius R
    - ✓ Height L



- Physical processes
  - Particle injection (source)
  - Spatial diffusion
  - Energy transport and losses
  - Scattering and/or annihilation
  - Galactic wind away from the disk in vertical direction
  - Reacceleration on random hydrodynamic waves

$q_{\bar{p}}^{\rm DM}(r,z,T_{\bar{p}})$ — Propagation in the Galaxy → $\Phi^{\bar{p}}(r,z,T_{\bar{p}})$

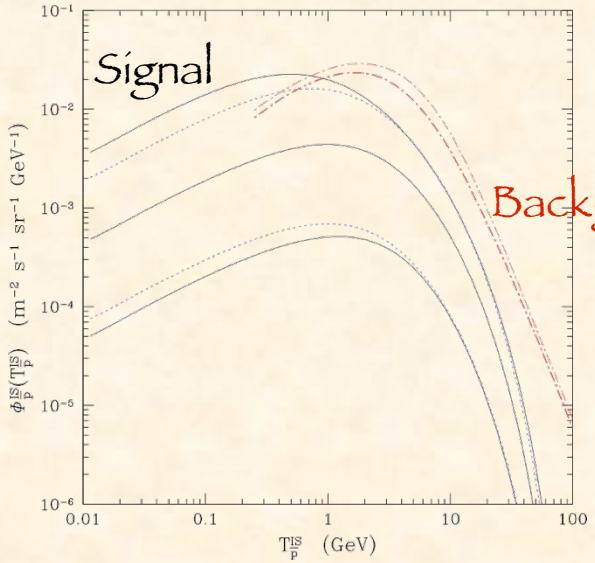
- solution of the steady-state diffusion equation with energy losses and reacceleration
- depends on a number of astrophysical parameters:
  - diffusion coefficient $K(E) = K_0 \beta (\mathcal{R}/1\,\mathrm{GV})^{\delta}$
  - height of the diffusive halo L
  - galactic wind velocity V_c
  - Alfven velocity (reacceleration) V_A

The params are constrained by stable nuclei propagation, mainly B/C

[D. Maurín et al. Astron. Astrophys. 381 (2002) 539]

case	δ	K_0 (kpc^2/Myr)	L (kpc)	V_c (km/sec)	V_A (km/sec)	$\chi^2_{\rm B/C}$
max	0.46	0.0765	15	5	117.6	39.98
med	0.70	0.0112	4	12	52.9	25.68
min	0.85	0.0016	1	13.5	22.4	39.02

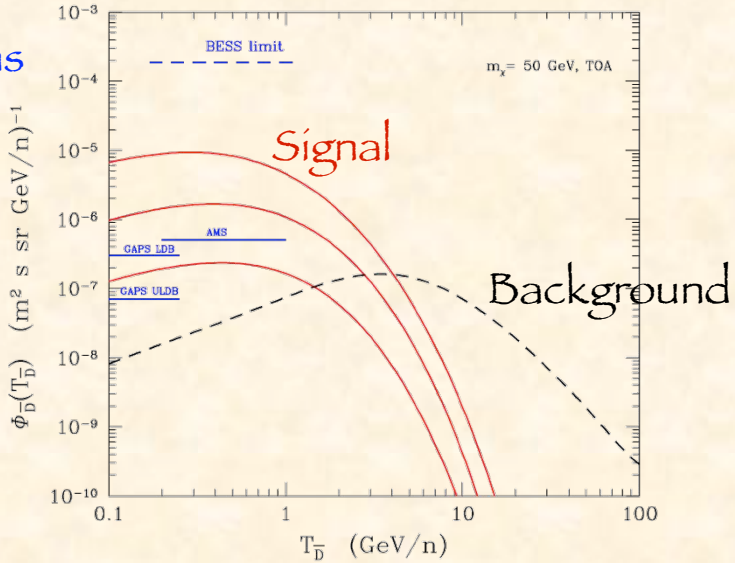
Astrophysical uncertainties on DM signals



Antiprotons

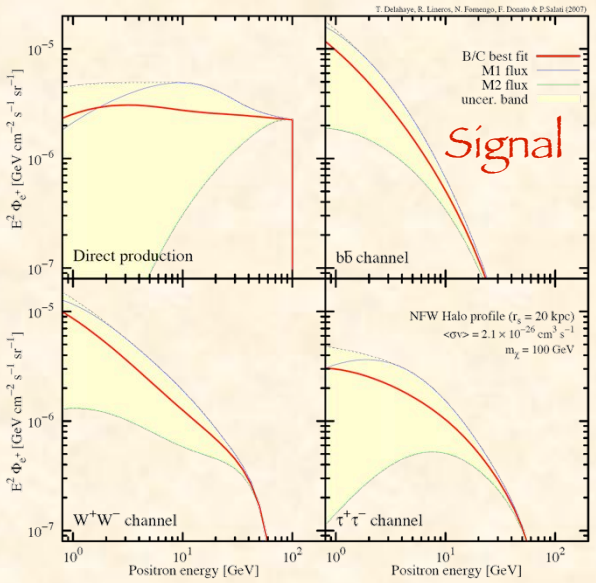
Antideuterons

m_X = 50 GeV



Positrons

m_X = 100 GeV



F. Donato, N. Fornengo, P. Salati, PRD 62 (2000) 043003

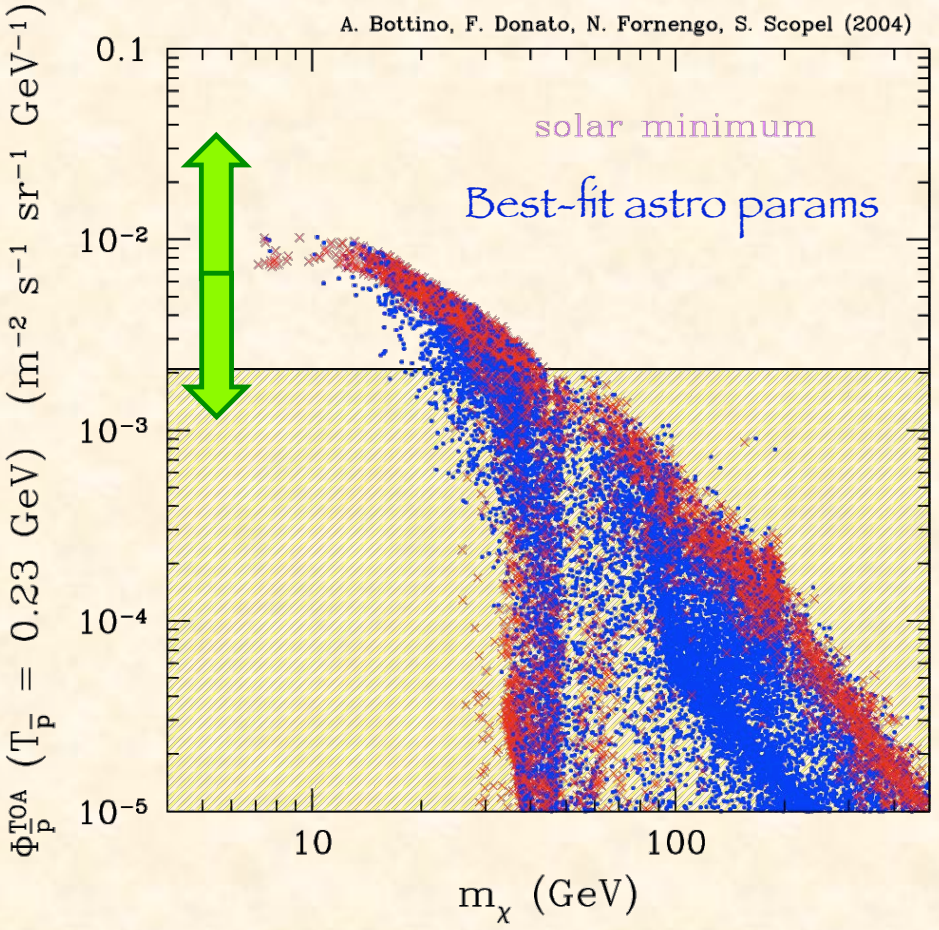
F. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

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

Cosmic antiprotons

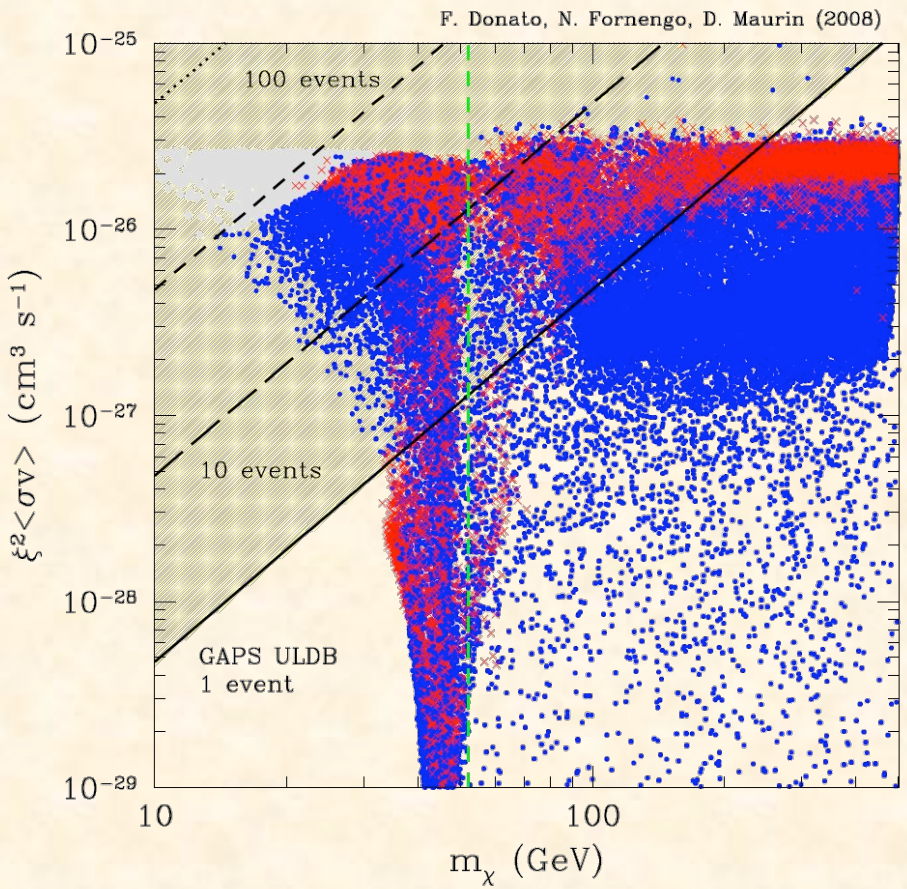
MSSM + gaugino non universal



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

Cosmic antideuterons

MSSM + gaugino non universal



Best-fit astro params

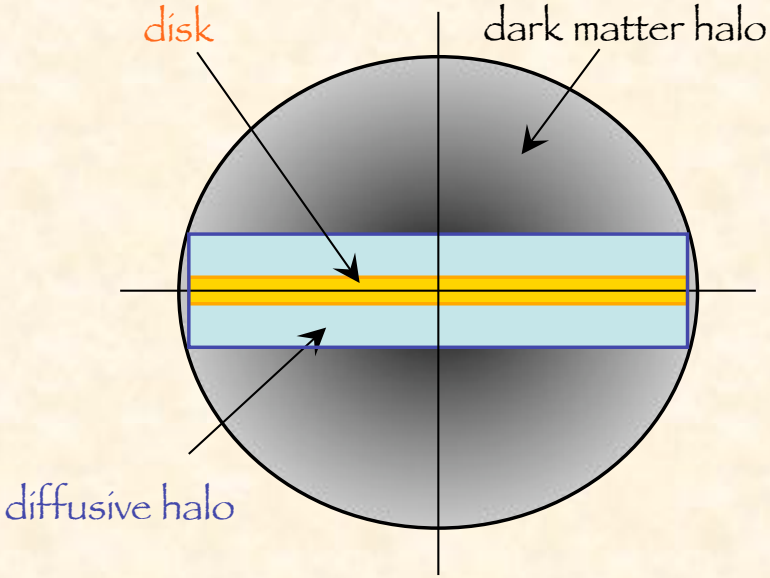
F. Donato, N. Fornengo, D. Maurin, PRD 78 (2008) 043506

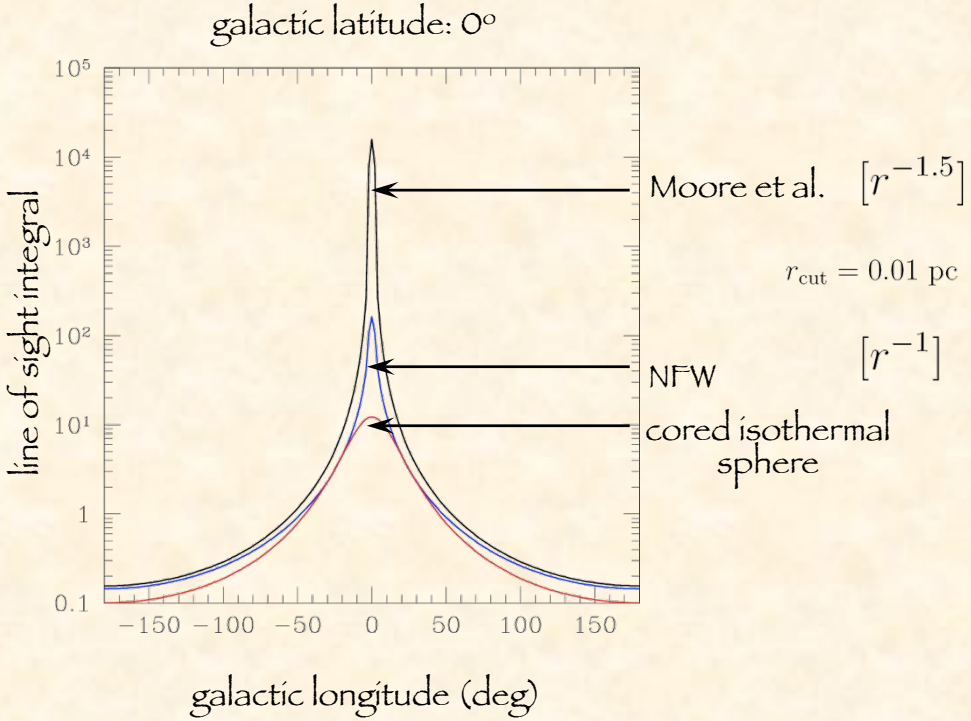
DM Code: Indirect Detection

- Galactic antiprotons, antideuterons, positrons, electrons
  - Source spectra modeled from PYTHIA (fitted; library)
  - Galactic transport in a 2-zone diffusion model (*) for various DM profiles
  - [Astrophysical backgrounds are also calculated]
- Gamma-rays
  - Spectra modeled from PYTHIA (fitted; library)
  - LoS for various DM profiles

(*) Galactic propagation: implements the results from the collaboration with P. Salati, D. Maurin, R. Taillet, T. Delahaye, J. Lavalle

Gamma-rays





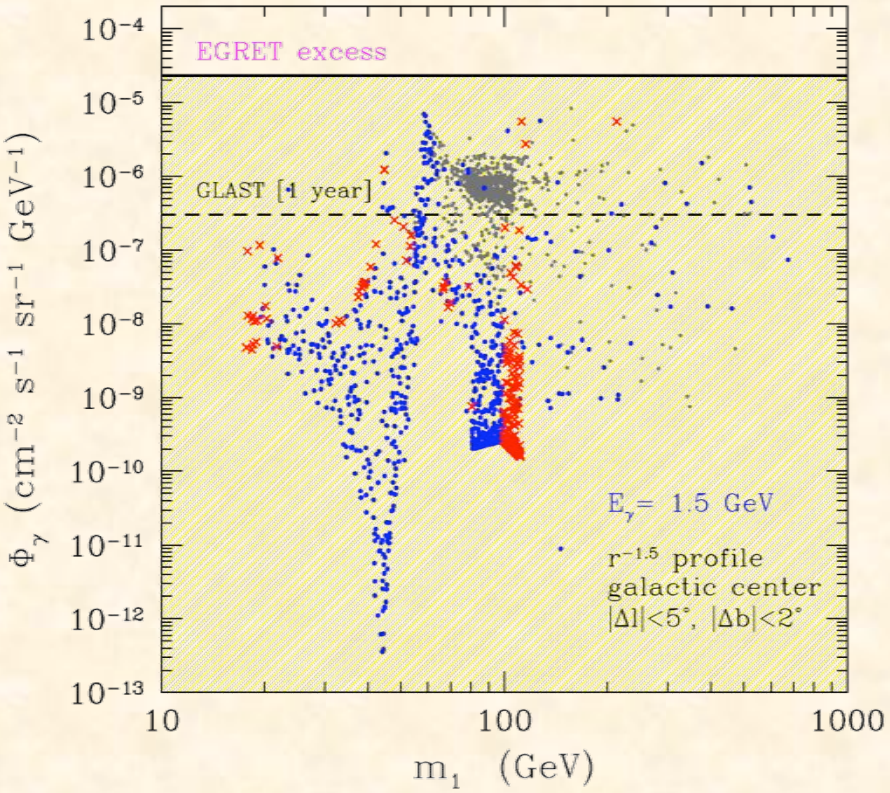
DM signal

$$\chi\chi \longrightarrow (.....) \longrightarrow \gamma \quad \text{diffuse}$$

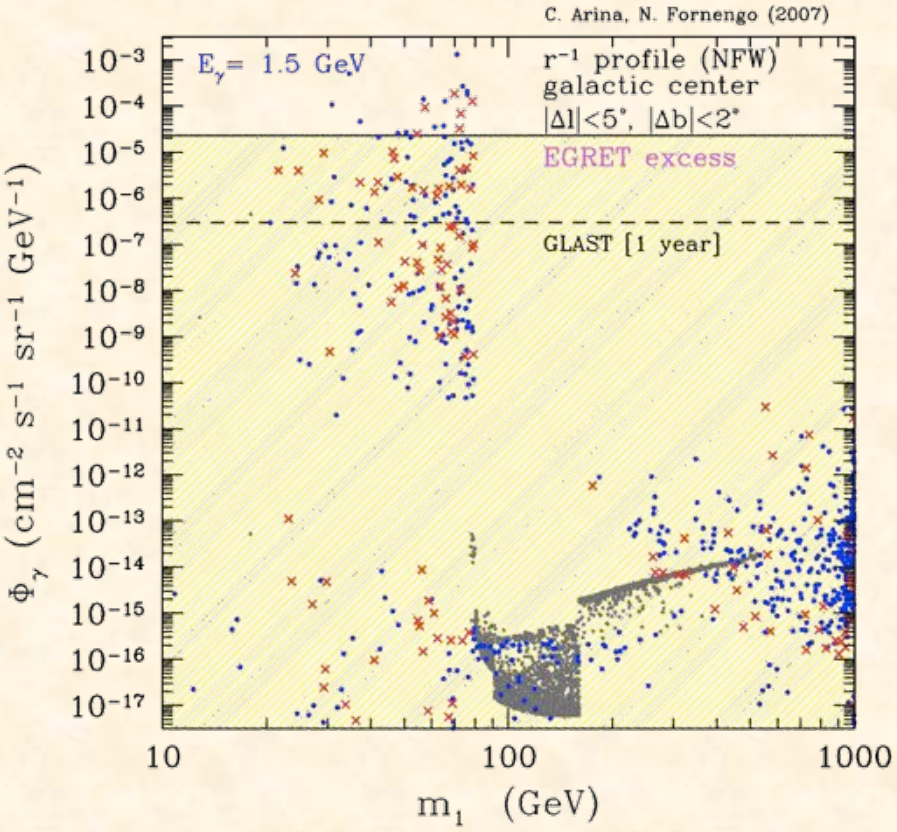
$$\chi\chi \longrightarrow [1\ loop] \longrightarrow 2\gamma \quad \text{line}$$

The flux is sensitive to the DM density profile

Sneutrino Dark Matter: Gamma-Rays



Left-right models



"Majorana" models

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

DM Code: Indirect Detection

- Galactic antiprotons, antideuterons, positrons, electrons
  - Source spectra modeled from PYTHIA (fitted; library)
  - Galactic transport in a 2-zone diffusion model (*) for various DM profiles
  - [Astrophysical backgrounds are also calculated]
- Gamma-rays
  - Spectra modeled from PYTHIA (fitted; library)
  - LoS for various DM profiles
- Neutrinos from Earth and Sun
  - Capture rate for isothermal sphere
  - Neutrino spectra modeled from PYTHIA (fitted; library)
  - Neutrino oscillations in 3 families included
  - Signal events: stopping and through-going muons

(*) Galactic propagation: implements the results from the collaboration with P. Salati, D. Maurin, R. Taillet, T. Delahaye, J. Lavalle

Neutrino Production

- Neutrinos are produced by DM annihilation
  - Available channels depend on mass threshold

$$\chi\chi \to \nu\nu,\ l\bar{l},\ q\bar{q},\ W^+W^-,\ ZZ,\ \text{Higgses},\ \text{Higgs} + \text{gauge}$$

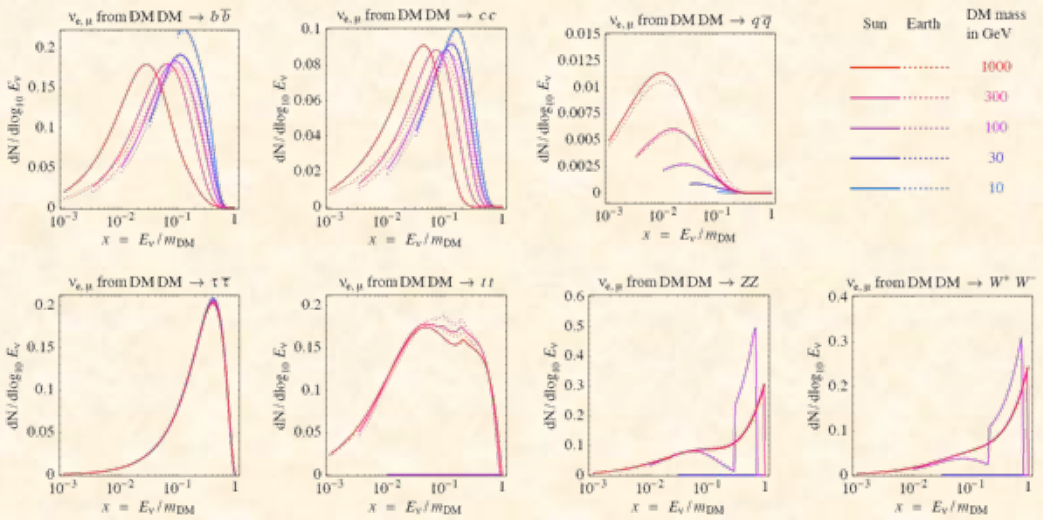
  - Quark hadronize → neutrinos from hadron decay

- Productions in Earth
  - Muons: stopped before decay → neutrinos below typical thresholds
  - Taus: decay almost as in vacuum
  - Light hadrons: typically stopped before decay
  - Heavy hadrons: typically decay before loosing significant energy

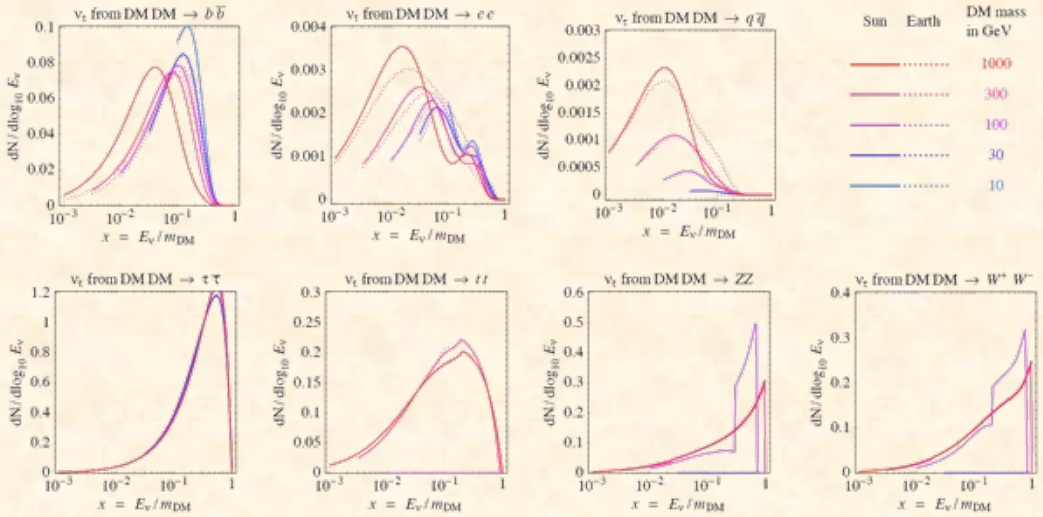
- Production in Sun
  - Leptons: stopping power of medium is stronger → softer neutrino spectra
  - Light hadrons: typically stopped before decay
  - Heavy hadrons: energy losses important, need modeling

Spectra at production

ν_e, ν_μ



ν_τ



M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

Neutrino propagation

Density matrix evolution

neutral-current processes

$$\frac{d\boldsymbol{\rho}}{dr} = -i[\boldsymbol{H},\ \boldsymbol{\rho}] + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm CC} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm NC} + \left.\frac{d\boldsymbol{\rho}}{dr}\right|_{\rm in}$$

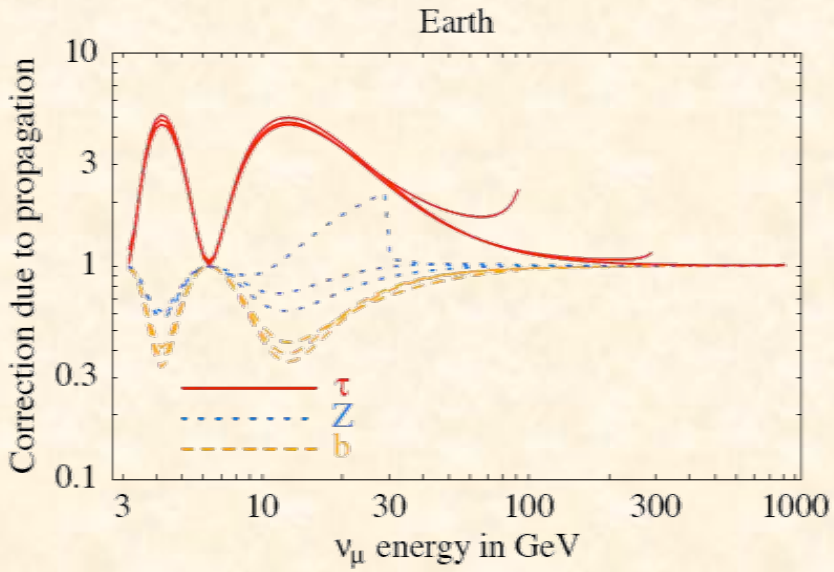
charged-current processes

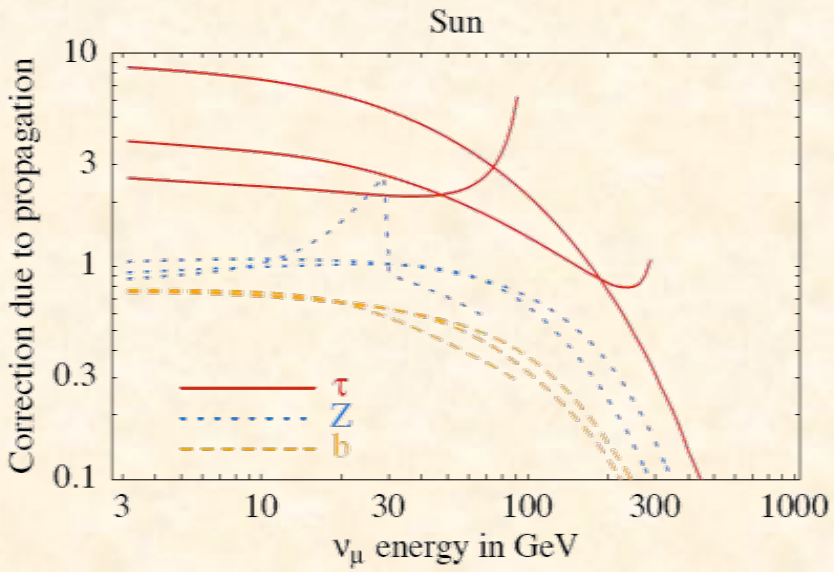
source

Vacuum oscillations and MSW matter effect

$$\boldsymbol{H} = \frac{\boldsymbol{m}^\dagger \boldsymbol{m}}{2E_\nu} + \sqrt{2} G_{\rm F} \left[N_e \ {\rm diag}\,(1,0,0) - \frac{N_n}{2}\ {\rm diag}\,(1,1,1) \right]$$

Effect of propagation





Earth:

- Affected only by "atmospheric" oscillation $\nu_\mu \leftrightarrow \nu_\tau$ at $E < 100$ GeV

Sun:

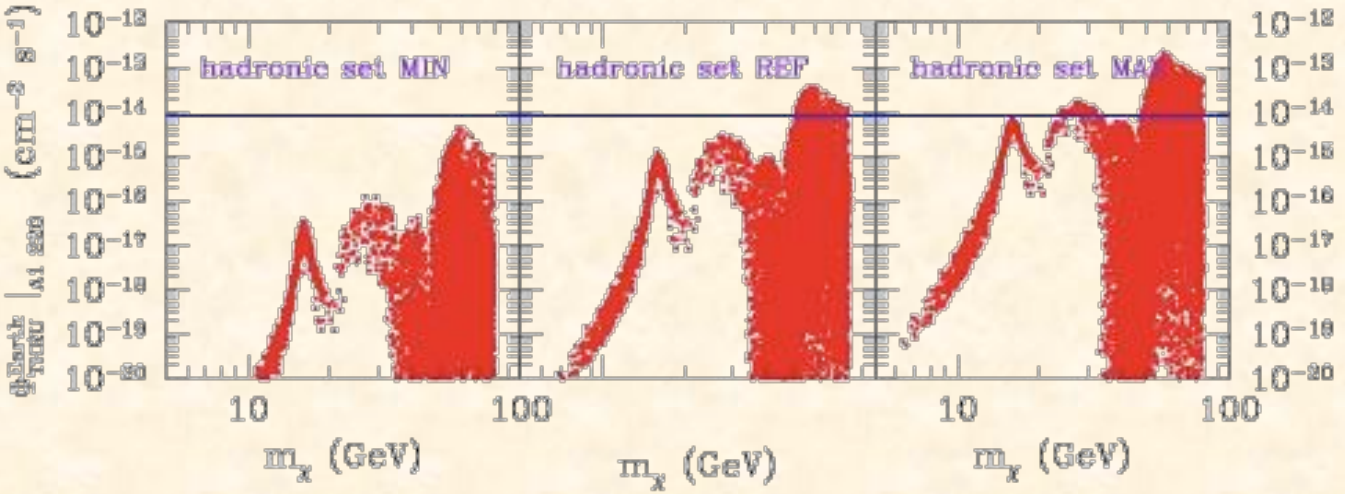
- Affected by average "solar" and "atmospheric" oscillations
- Absorption suppresses neutrinos for $E > 100$ GeV (partially converted to lower energy neutrinos (by NC and regeneration)

M. Cirelli, N.Fornengo, T. Montaruli, I. Sokalski, A. Strumia, F. Vissani, NPB 727 (2005) 99

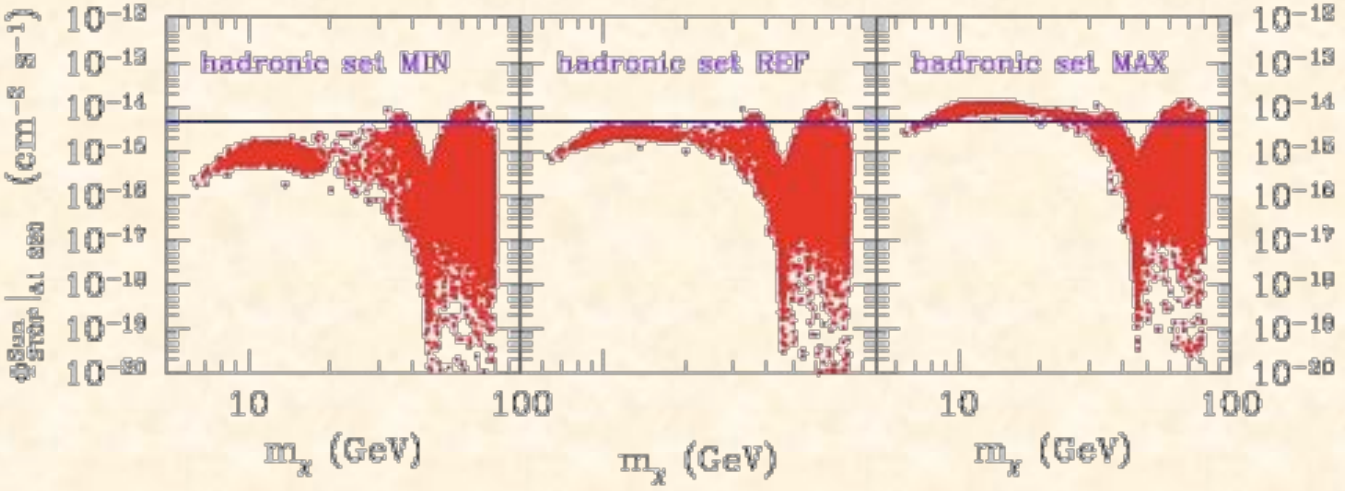
See also: M. Blennow, J. Edsjo, T. Ohlsson, JCAP 0801 (2008) 021 for an event-based MC approach

Signals at neutrino telescopes

Earth
Thru-going muons



Sun
Stopping muons



Future improvements

- Extension of the study of sneutrino DM
  - New models
  - Gamma-ray line
- Multi-wavelength signals: radio, X, SZ on CMB
- Reanalysis of the antideuteron signal
- Refinement on the galactic propagation of charged cosmic rays
- Directionality in direct detection
- DM distributions from updated numerical simulations

(...)