Detecting WIMPs with MeV neutrinos from the Sun

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DARK MALT
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MIAPP Munich Institute for Astro- and Particle Physics

Usually only considered annihilations into
heavy quarks, gauge bosons or tau leptons...

Why not annihilations into light quarks, muons or electrons?

- **Electrons/positrons do not produce neutrinos...**
- **Muons lose energy electromagnetically very rapidly and decay at rest**

$$\tau_{stop} \approx 3 \cdot 10^{-10} \left(\frac{E}{10\ \text{GeV}} \right) s \ll \tau_{decay} \approx 2 \cdot 10^{-4} \left(\frac{E}{10\ \text{GeV}} \right) s$$

- **Light-quark hadrons, as pions, are stopped via nuclear interactions and decay at rest**

$$\tau_{\text{int}} \approx 10^{-11}\, s \ll \tau_{decay} \approx 10^{-6} \left(\frac{E}{10\ \text{GeV}} \right) s$$

Usually only considered annihilations into
heavy quarks, gauge bosons or tau leptons...

Why not annihilations into light quarks, muon

- Electrons/positrons do no

What about the low-energy neutrinos from pion and muon decay at rest?

This is a novel way to constrain DM

N. Bernal, J. Martín-Albo and SPR, JCAP 1308:011, 2013

(see also C. Rott, J. Siegal-Gaskins and J. F. Beacom, Phys. Rev. D88:055005, 2013)

- nuclear interactions

$$\tau_{\mathrm{int}} \approx 10^{-11}\, s \;\ll\; \tau_{decay} \approx 10^{-6} \left(\frac{E}{10\ \mathrm{GeV}} \right) s$$

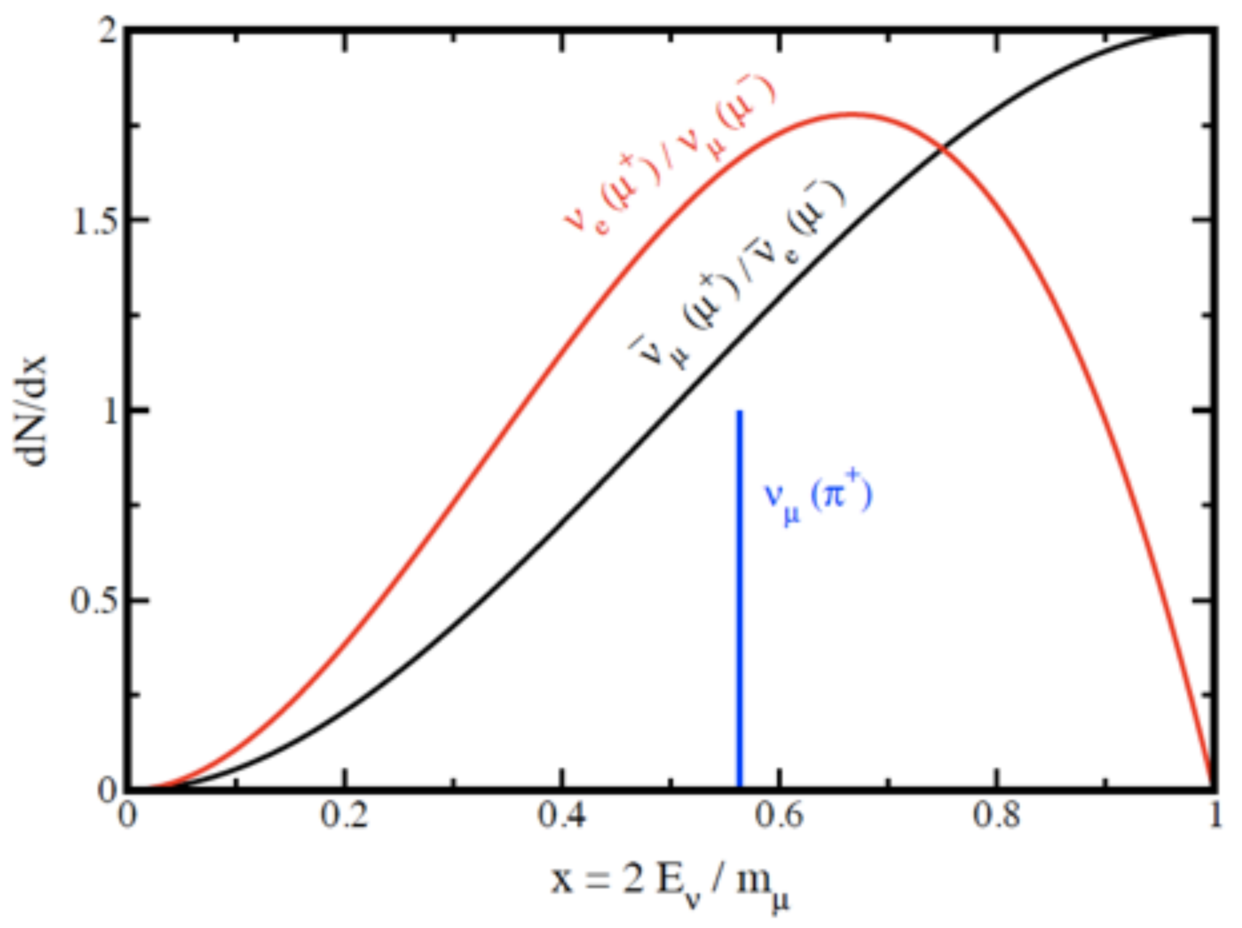
- Electrons/positrons, in their propagation in the Sun, could produce pions, which then can decay at rest
- Muons lose energy electromagnetically and decay at rest
- Pions get stopped

  π^+ decay at rest

  π^- are captured by nuclei and practically all get absorbed

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



Procedure: initial neutrino fluxes

- For each WIMP mass, we consider the averaged density and composition according to their distribution in the Sun

- We simulate all the particles propagation in the Sun with GEANT4

- For the case of annihilations into a pair of leptons, we inject the two leptons with energies equal to the WIMP mass directly into GEANT4 and let them propagate

- For the case of annihilations into quarks, we follow two steps:

  1. We use PYTHIA 6.4 to hadronize and fragment the initial quarks and do not let decay any of the final particles that are produced

  2. We inject into GEANT4 the full spectrum of all the produced particles and simulate their propagation

- Finally, we count the number of pions and muons (of each charge) that decay at rest

Distribution of WIMPs in the Sun

We consider the optically thin and thick regimes and make a smooth matching in the intermediate regime

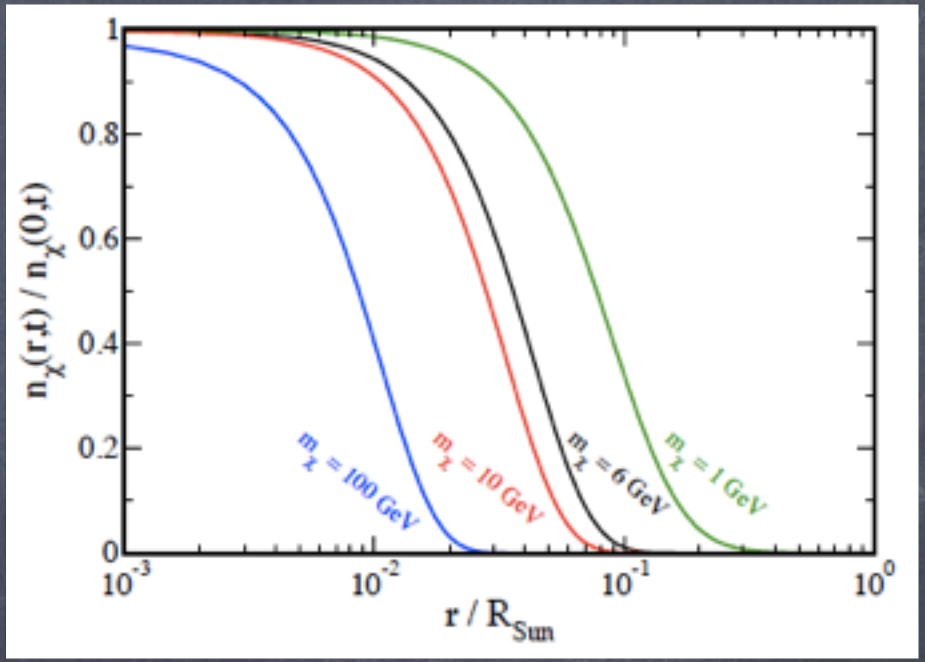
$$n_\chi(r) = f(K)\, n_{\chi,LTE}(r) + (1 - f(K))\, n_{\chi,iso}(r)$$

P. Scott, M. Fairnairn and J. Edsjö, *Mon. Not. Roy. Astron. Soc. 394:82, 2009*

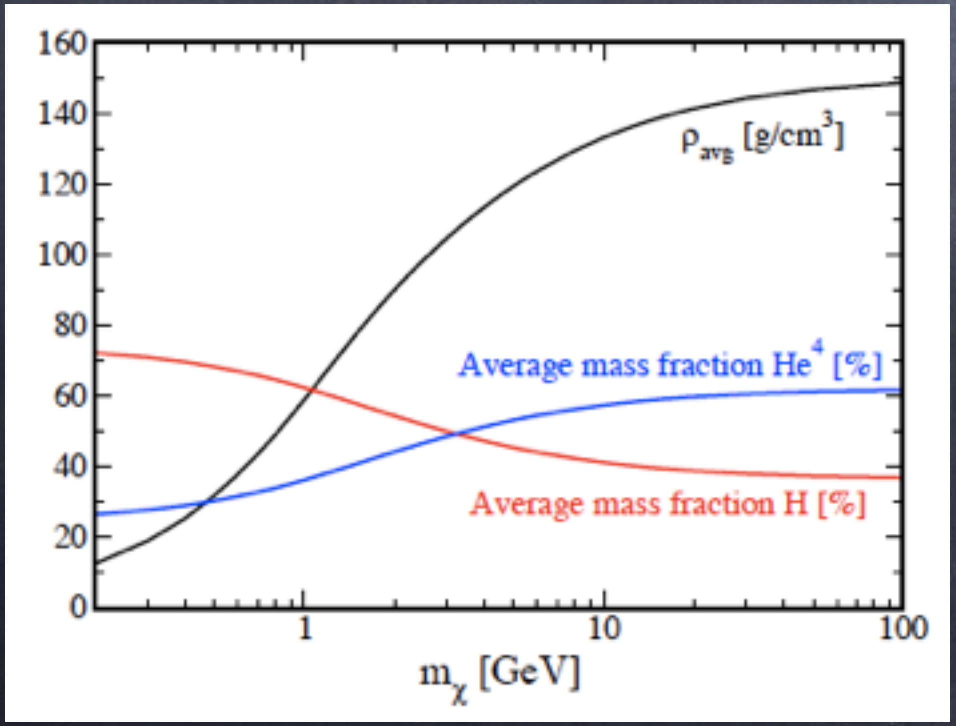
Close to isothermal distribution:

$$n_{\chi,iso}(r) \propto e^{-m_\chi \phi(r)/T_\chi(m_\chi)}$$

D. N. Spergel and W. H. Press, *Astrophys. J. 294:663, 1985*
J. Faulkner and R. L. Gilliland, *Astrophys. J. 299:994, 1985*



Average density and composition:

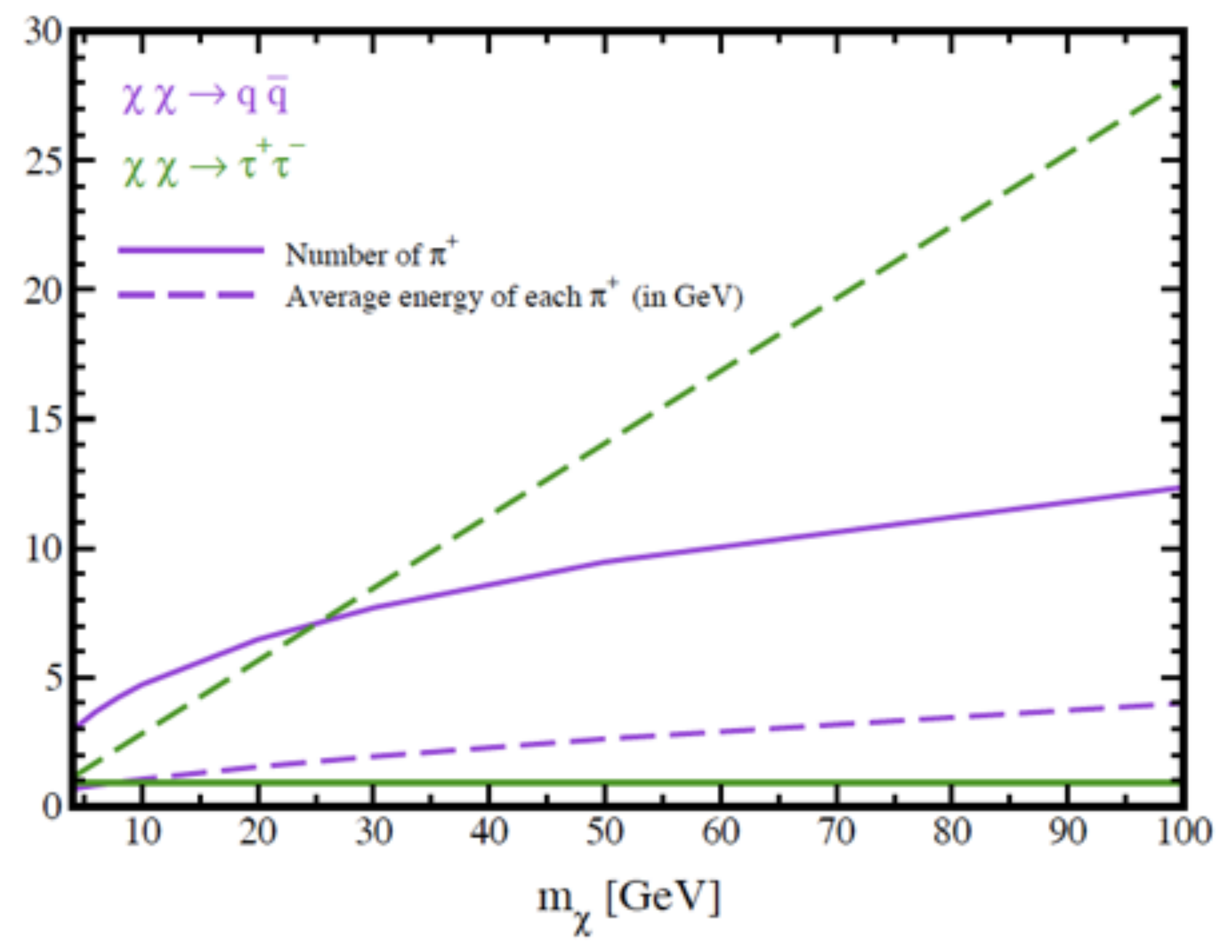


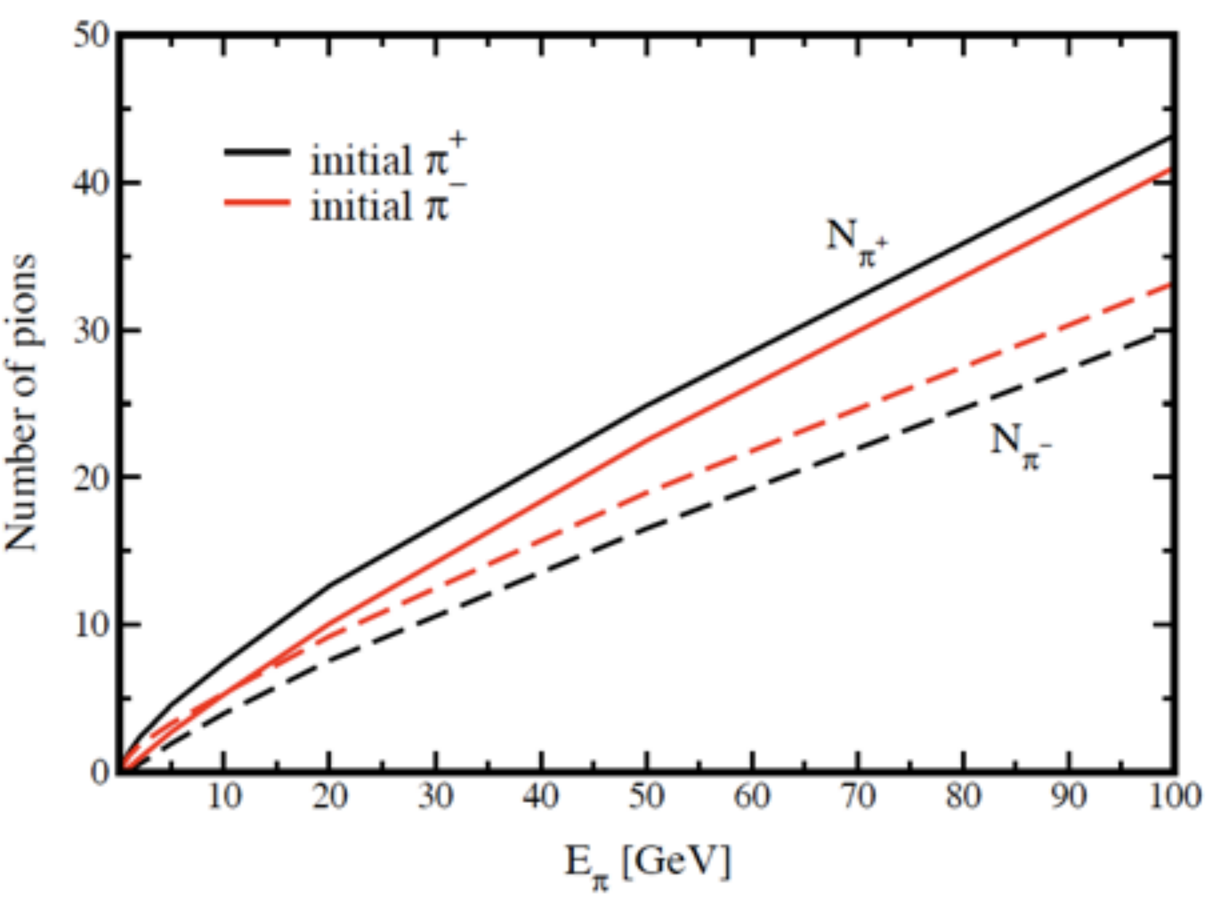
Only shown the two main elements, although we take 29 in our computations

From
M. Asplund, N. Grevesse, A. J. Sauval and P. Scott, *Ann. Rev. Astron. Astrophys. J. 47:481, 2009*
A. M. Serenelli, W. C. Haxton and C. Peña-Garay, *Astrophys. J. 743:24, 2011*

Pions production in the Sun

(Approximate) Number of pions and average energy just after WIMPs annihilations

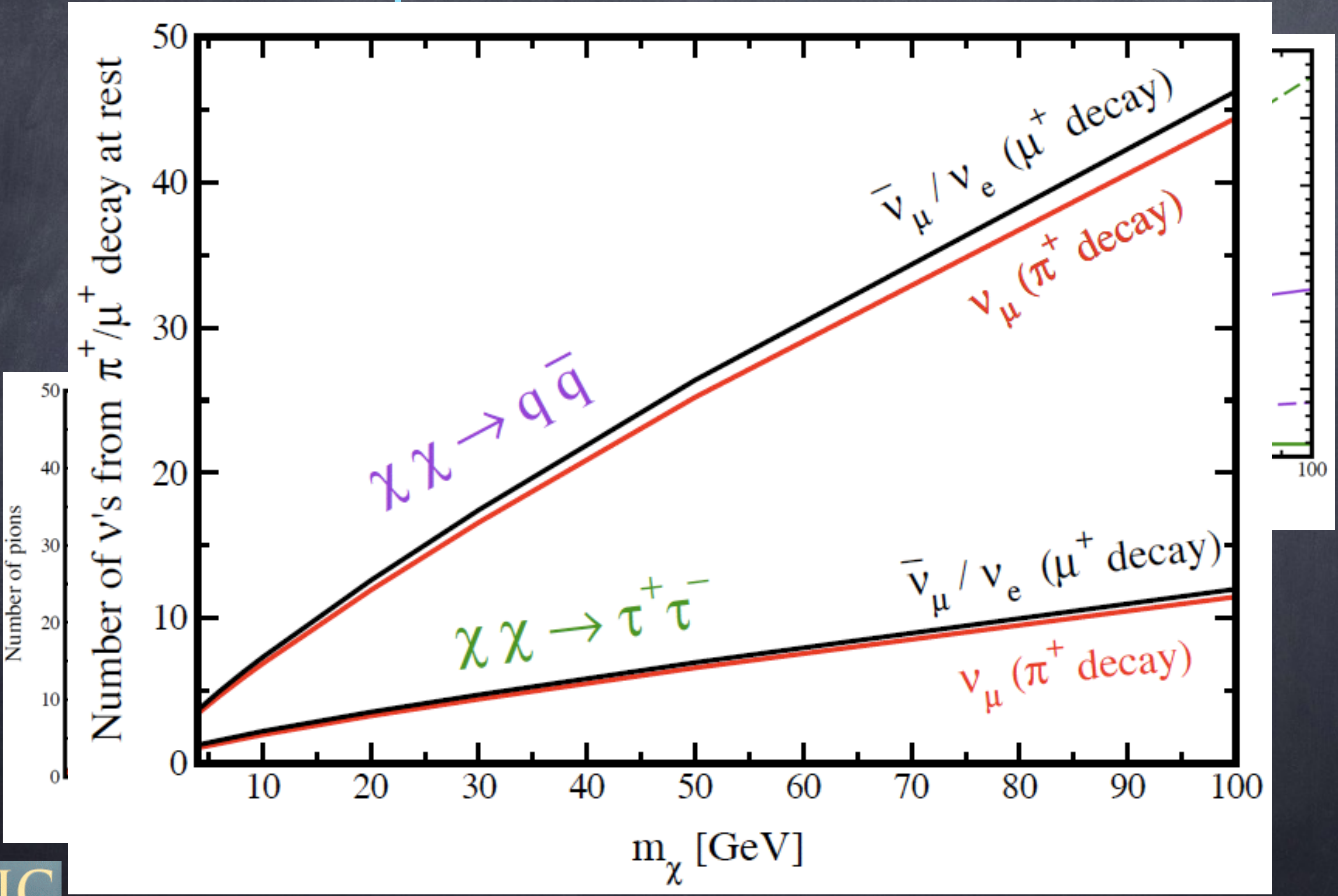




Number of pions produced after propagation of a single pion of a given energy

N. Bernal, J. Martín-Albo and SPR, *JCAP 1308:011, 2013*

Pions production in the Sun



Neutrino propagation through the Sun

Matter effects dominate:

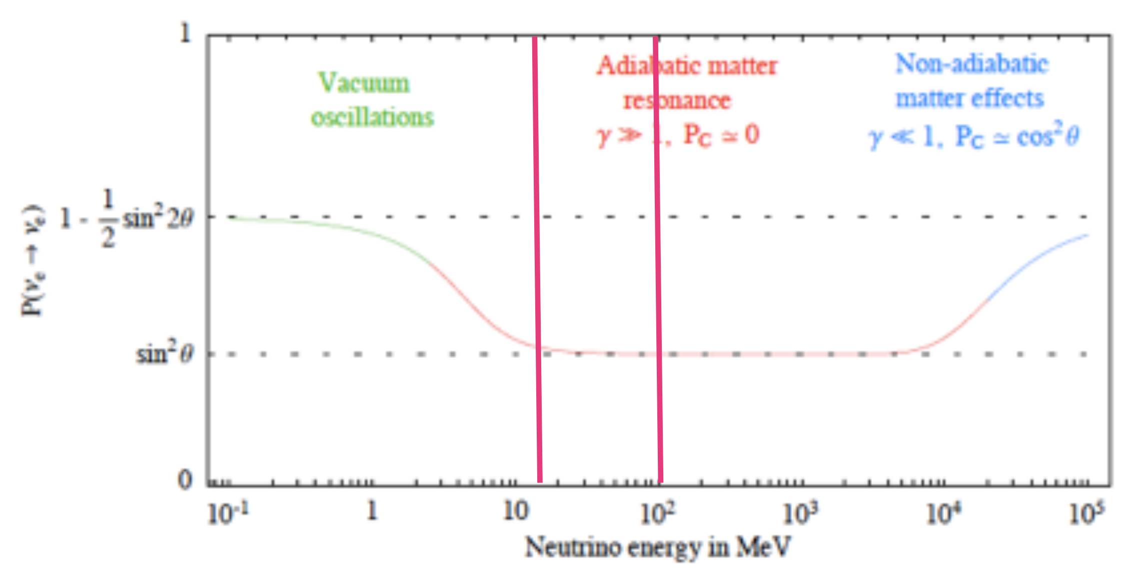
$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta \mp 2\sqrt{2} G_F N_e E} \longrightarrow$$

$\cos 2\theta_m \simeq -1$ neutrinos

$\cos 2\theta_m \simeq +1$ antineutrinos

The propagation is adiabatic:

$\nu_e \left(\bar{\nu}_e\right)$ exit the Sun as almost purely $\nu_2 \left(\nu_1\right)$ and $\nu_\mu \left(\bar{\nu}_\mu\right)$ almost as an equal mixture of $\nu_1 \left(\nu_2\right)$ and ν_3



A. Strumia and F. Vissani, *arXiv:hep-ph/0606054*

Probabilities at detection

(neglecting the Earth-matter effect)

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \cos^2\theta_{23}\sin^2\theta_{12}\cos^2\theta_{13} + \sin^2\theta_{13}\cos^2\theta_{13}\sin^2\theta_{12}(1+\cos^2\theta_{12}) \simeq 0.180$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \cos^2\theta_{12}\cos^2\theta_{13} + \sin^4\theta_{13} \simeq 0.646$$

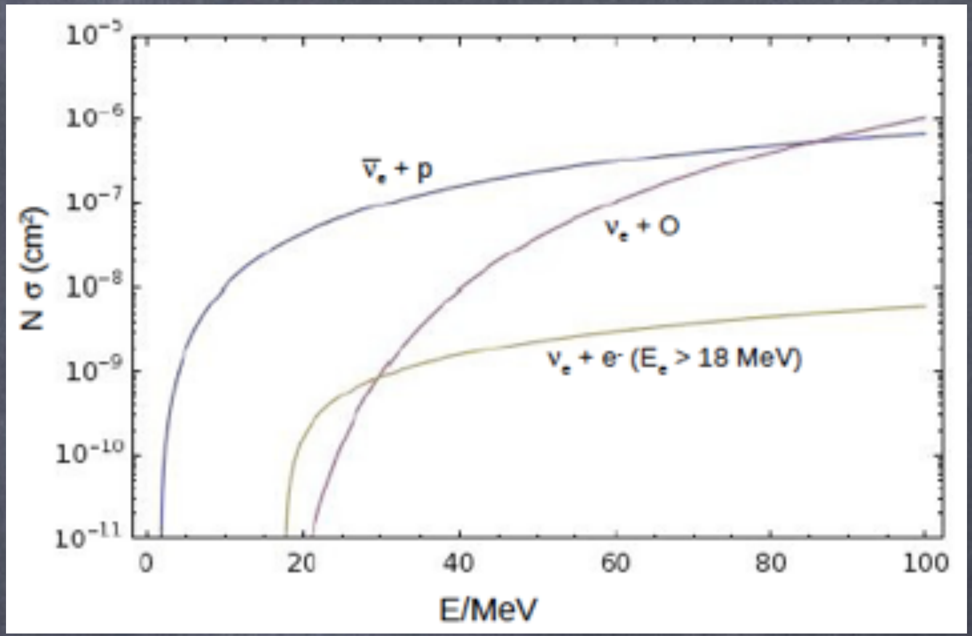
$$P(\nu_\mu \to \nu_e) = \cos^2\theta_{23}\cos^2\theta_{12}\cos^2\theta_{13} + \sin^2\theta_{13}\cos^2\theta_{13}\sin^2\theta_{12}(1+\sin^2\theta_{12}) \simeq 0.354$$

$$P(\nu_e \to \nu_e) = \sin^2\theta_{12}\cos^2\theta_{13} + \sin^4\theta_{13} \simeq 0.304$$

Detection of MeV neutrinos with SK

Main signature of MeV neutrinos:
inverse-beta decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



C. Lunardini and O. L. G. Peres, *JCAP 0808:033, 2008*

We consider inverse-beta decay off free protons (antineutrinos), with the full differential cross section and
interactions off bound nucleons (neutrinos and antineutrinos), by implementing a relativistic Fermi gas model

Diffuse Supernova Neutrino Background searches:
3 phases: SK-I (1497 days), SK-II (794 days) and SK-III (562 days)

K. Bays *et al.* [Super-Kamiokande Collaboration], *Phys. Rev. D85:052007, 2012*

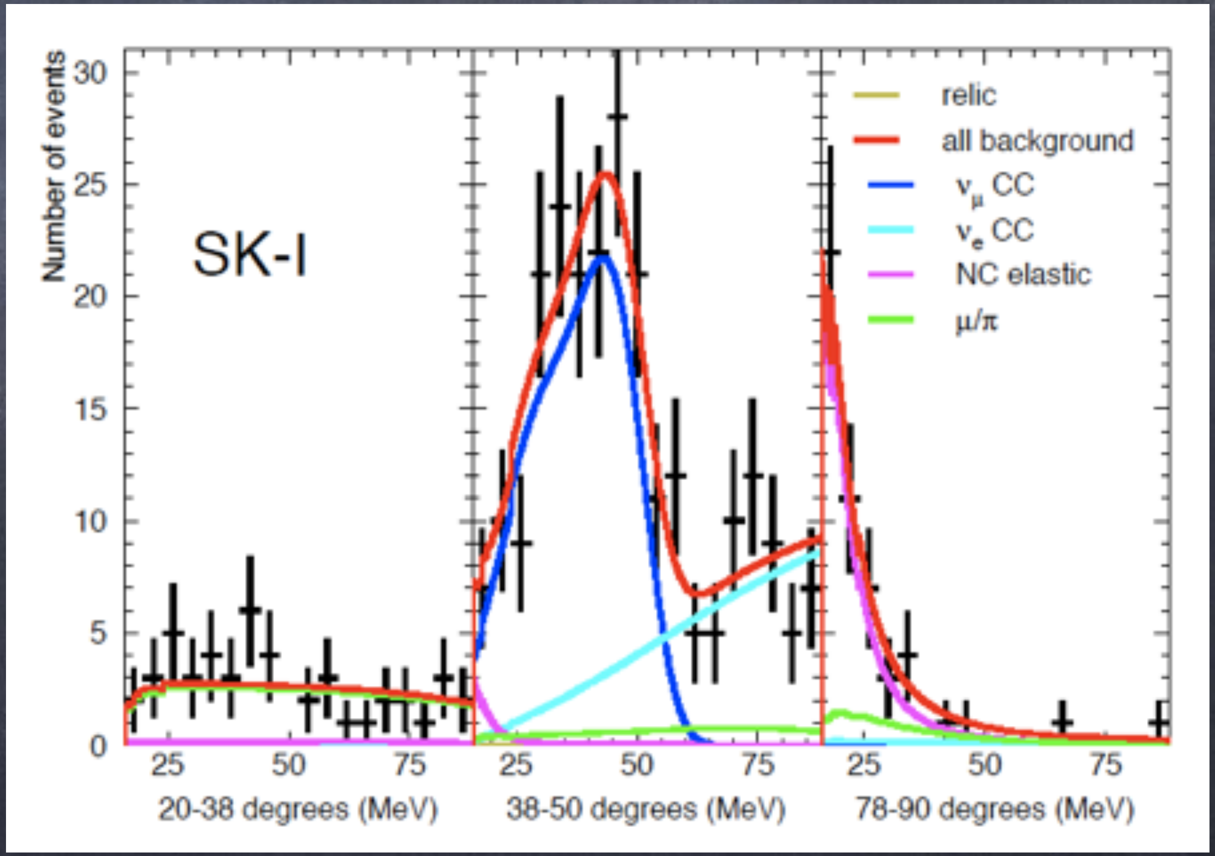
Two main backgrounds

- **Invisible muons: Michel positrons/electrons from the decays at rest of low-energy muons, produced by atmospheric muon neutrinos with energies up to about 400 MeV, which are below detection threshold (E < 160 MeV)**
- **Atmospheric electron neutrinos with energies up to about 350 MeV**

Two subdominant backgrounds

(also included in our analysis)

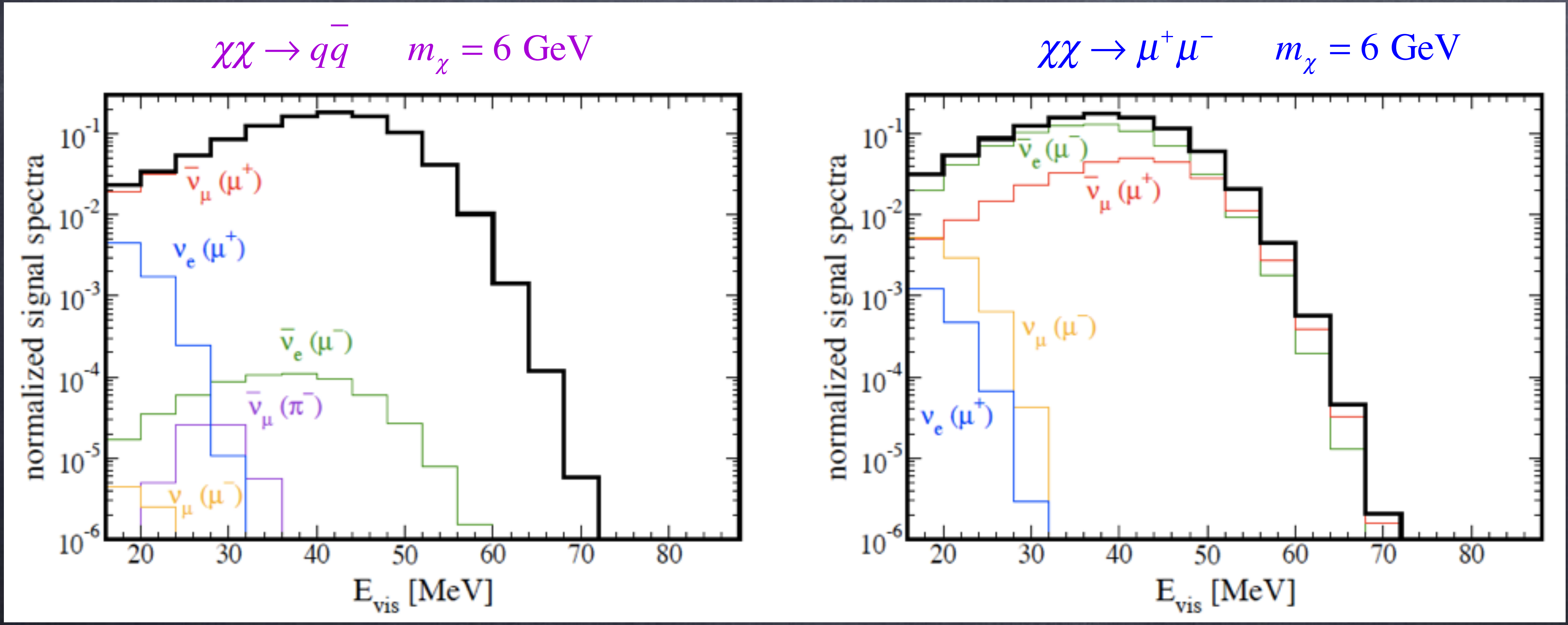
- **Atmospheric neutrino neutral current elastic events (important at high Cherenkov angles)**
- **muon/pion production from atmospheric neutrinos: pions and muons slightly above threshold misidentified as electrons (important at low Cherenkov angles)**



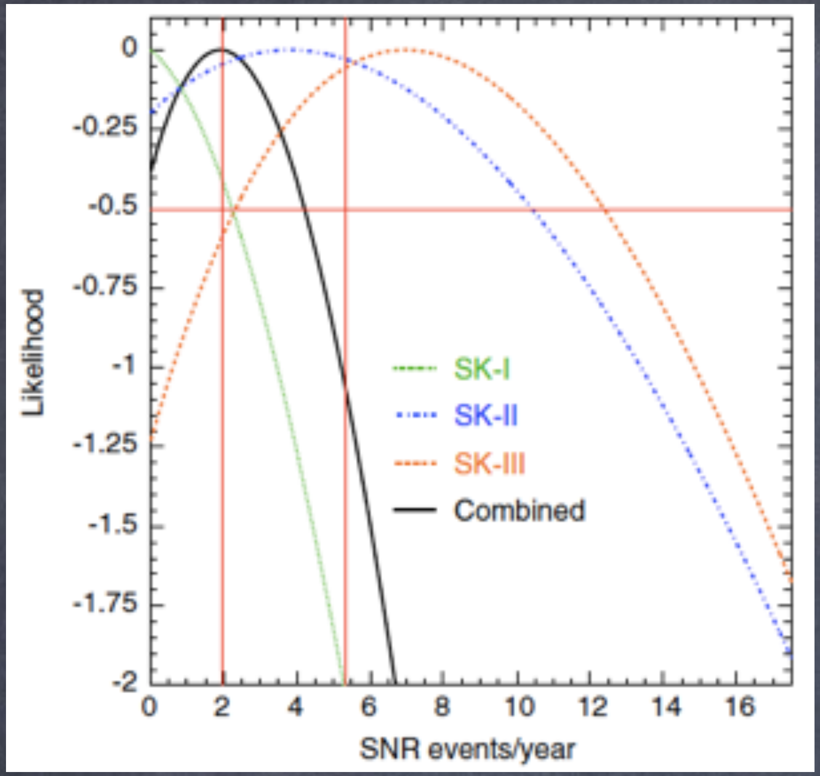
K. Bays *et al.* [Super-Kamiokande Collaboration], *Phys. Rev. D85:052007, 2012*

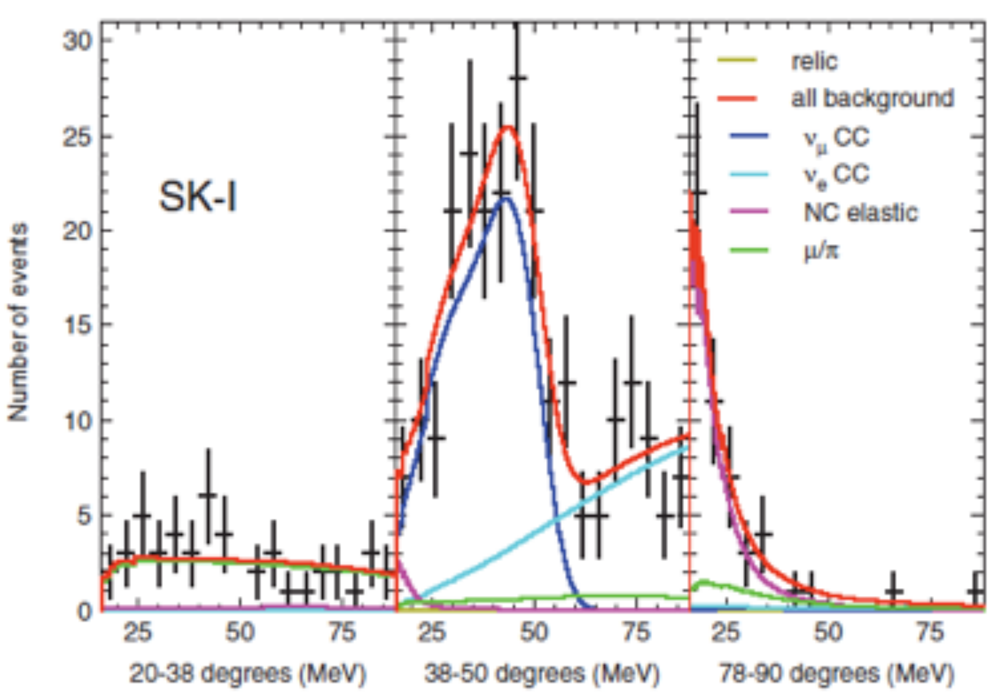
Spectrum of the potential signal at SK-I

$$A_l = A\int\left[\left(\frac{d\sigma_f^{\bar\nu}}{dE_e}(E_\nu,E_e)+\frac{1}{2}\frac{d\sigma_b^{\bar\nu}}{dE_e}(E_\nu,E_e)\right)\frac{d\phi^{\bar\nu}}{dE_\nu}(E_\nu)+\frac{1}{2}\frac{d\sigma_b^{\nu}}{dE_e}(E_\nu,E_e)\frac{d\phi^{\nu}}{dE_\nu}(E_\nu)\right]dE_e\,dE_\nu\times\int_{E_l}^{E_{l+1}}\varepsilon(E_{vis})R(E_e,E_{vis})\,dE_{vis}$$



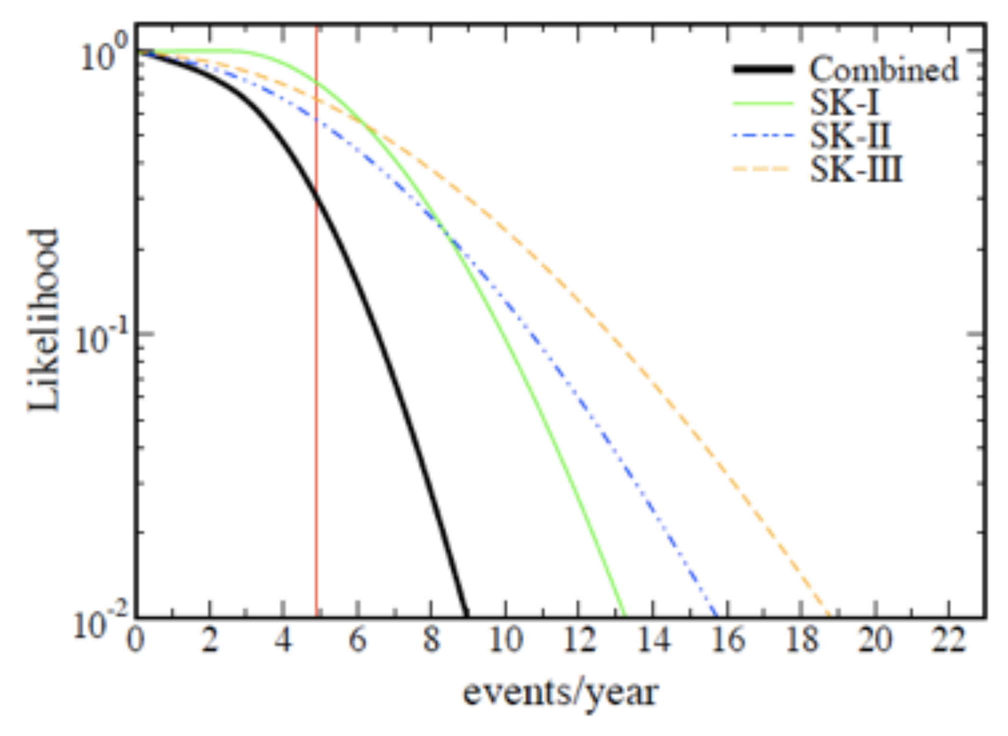
Diffuse Supernova Neutrino Background search

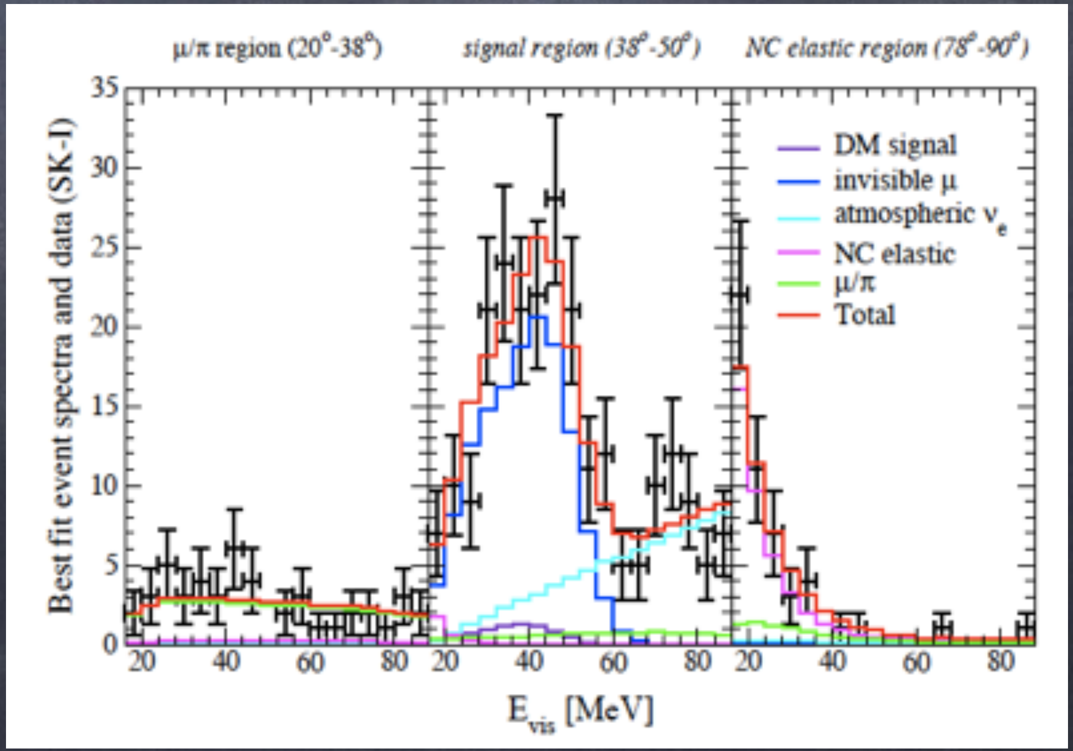




K. Bays *et al.* [Super-Kamiokande Collaboration], *Phys. Rev. D85:052007, 2012*

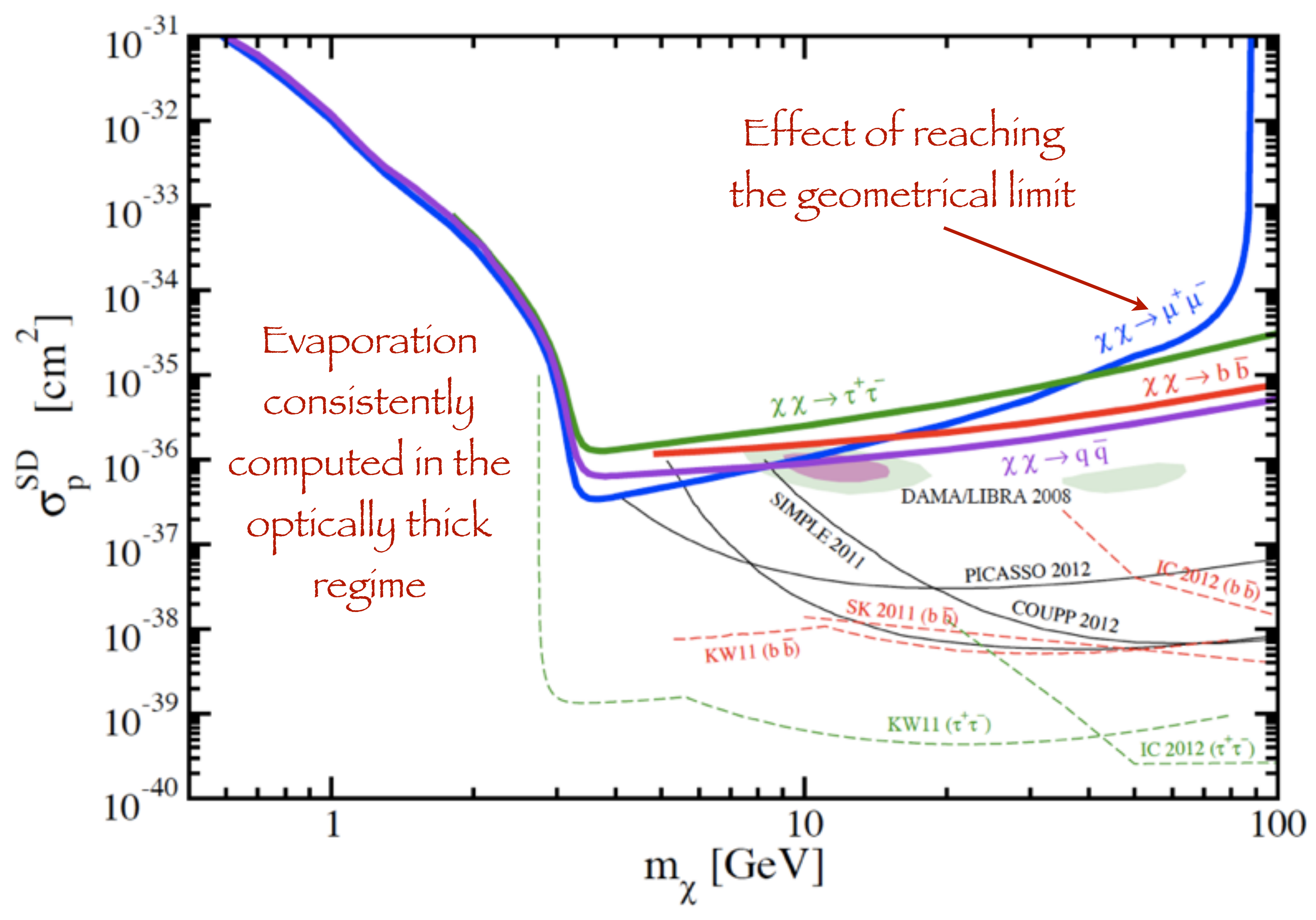
WIMPs annihilations in the Sun





N. Bernal, J. Martín-Albo and SPR, *JCAP 1308:011, 2013*

Limits on the SD scattering cross section



Effect of reaching the geometrical limit

Evaporation consistently computed in the optically thick regime

N. Bernal, J. Martín-Albo and SPR, *JCAP 1308:011, 2013*

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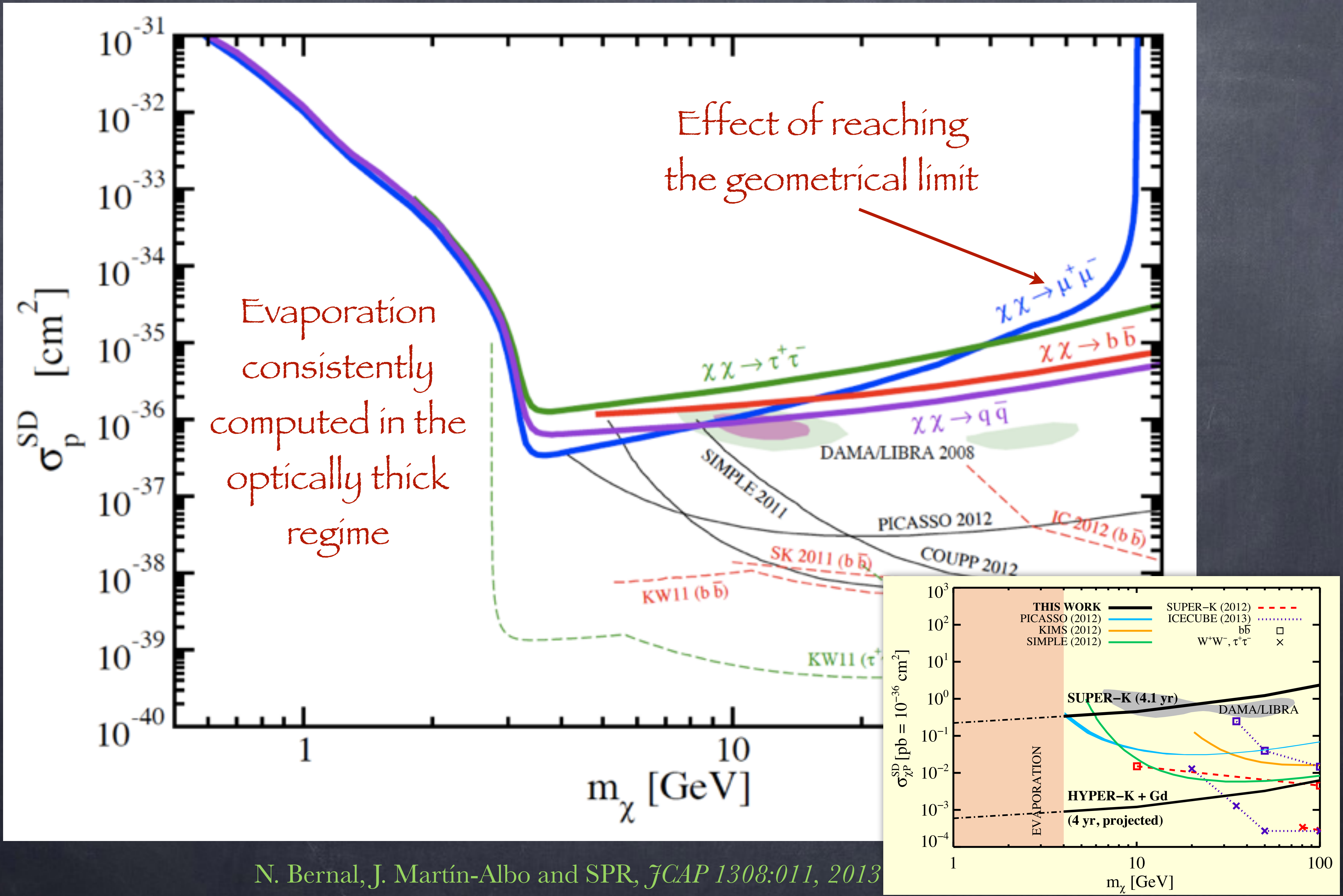

Effect of reaching
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Evaporation
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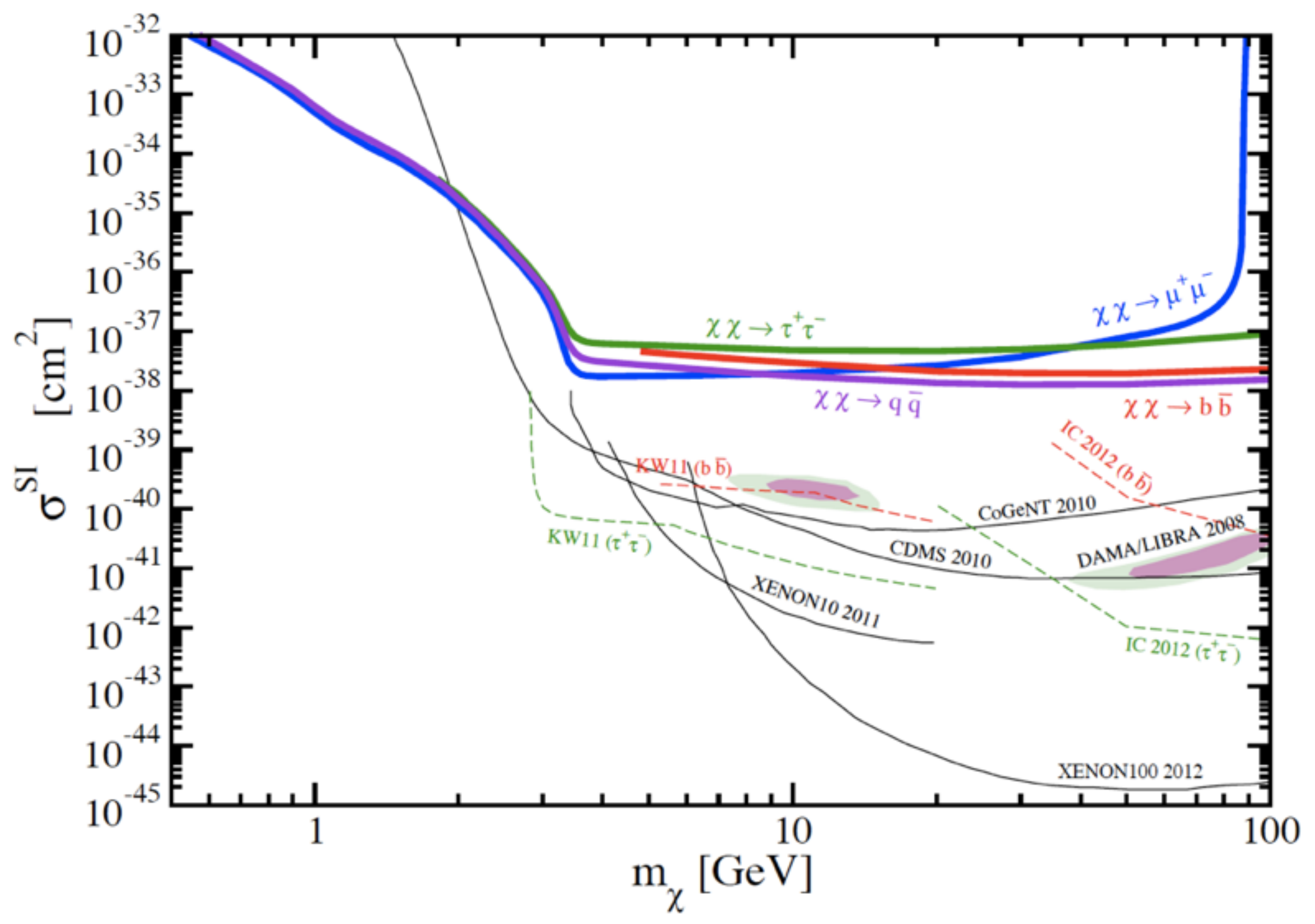
N. Bernal, J. Martín-Albo and SPR, *JCAP 1308:011, 2013*

See also: C. Rott, J. Siegal-Gaskins and J. F. Beacom, *Phys. Rev. D88:055005, 2013*

Limits on the SI scattering cross section



N. Bernal, J. Martín-Albo and SPR, *JCAP 1308:011, 2013*

Conclusions

- High-energy neutrinos from WIMPs annihilations in the Sun have been extensively studied

- However, these studies do not consider annihilations into electron/positron pairs, muons or light quarks

- A large amount of pions and muons would decay at rest (for any channel, except from annihilations into neutrinos) giving rise to a flux of MeV neutrinos

- We have used the SK analysis and data for the DSNB search and have set new limits on the scattering cross section of WIMPs off nucleons

- This is a novel way, never before explored, to set bounds on WIMPS, complementary to the limits from direct searches, mainly at low WIMP masses