A novel test of WIMPs annihilations in the Sun: MeV neutrinos

based on

N. Bernal, J. Martín-Albo and SPR, arXiv: 1208.0834

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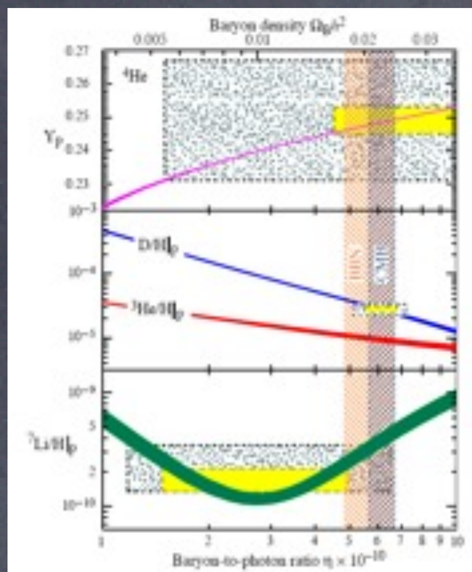
CFTP

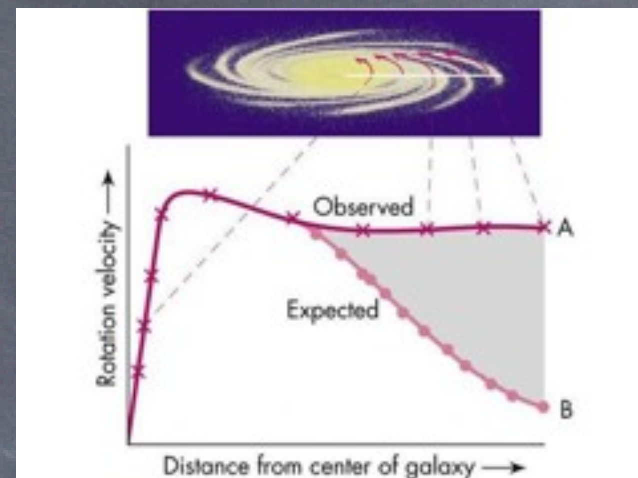
IPM
Institute for Research in Fundamental Sciences

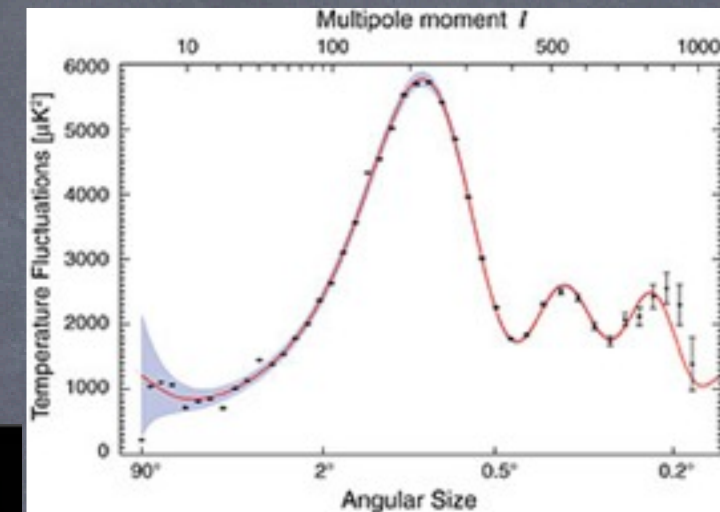
IPM international school and workshop on Particle Physics (IPP12):
Neutrino Physics and Astrophysics
Tehran, October 1, 2012

Astro/Cosmo Evidences of DM

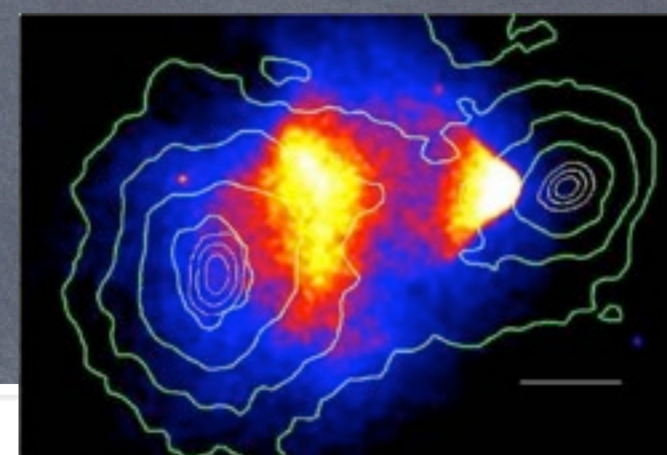


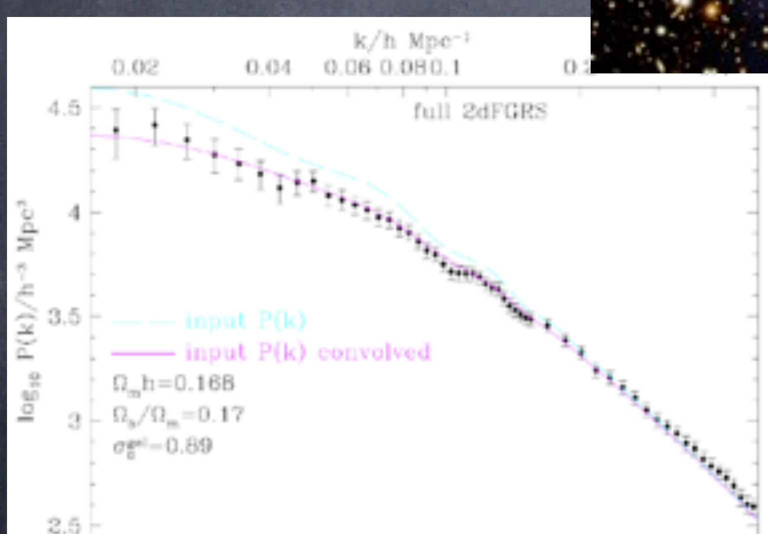
B. D. Fields and S. Sarkar, *PDG*



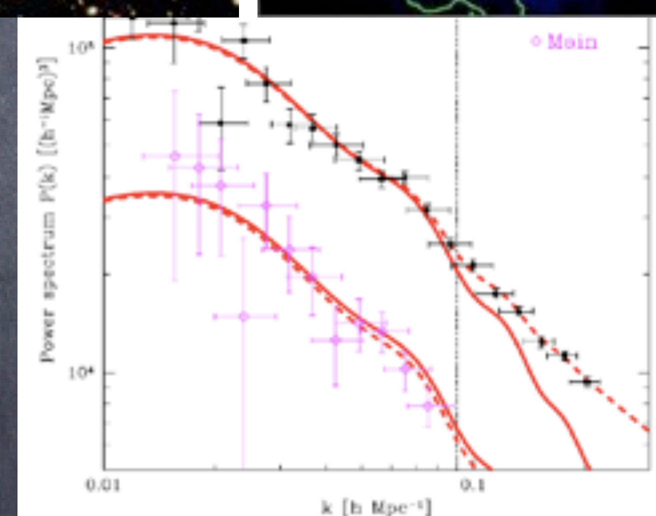


NASA/WMAP Science Team

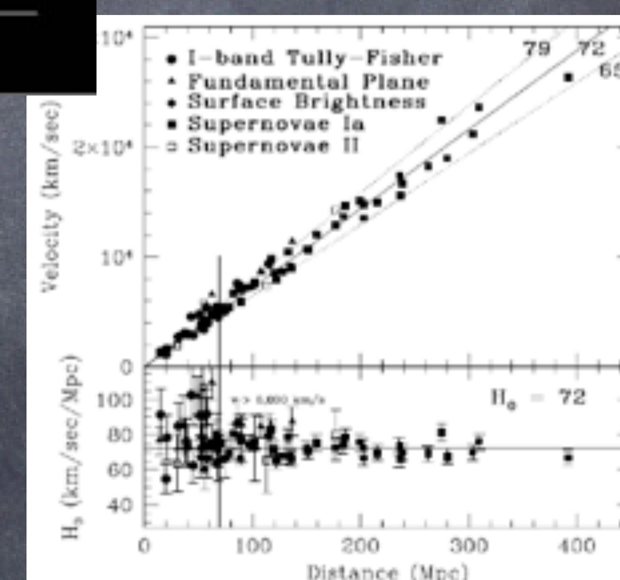




S. Cole *et al.* [2dFGRS Collaboration], *Mon. Not. Roy. Astron. Soc. 362:505, 2005*

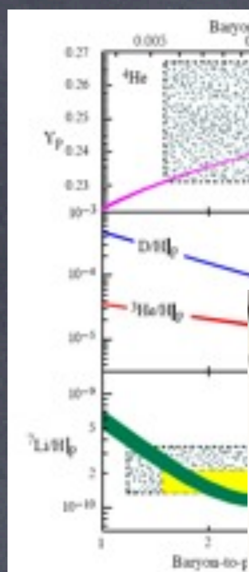


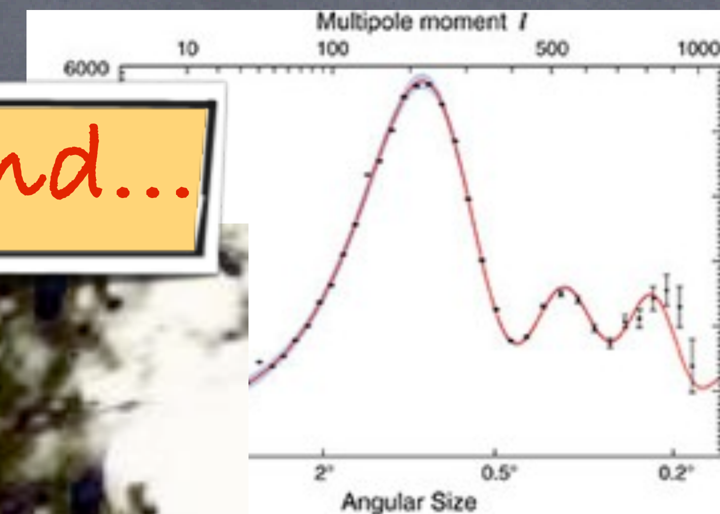
M. Tegmark *et al.* [SDSS Collaboration], *Phys. Rev. D74:123507, 2006*



W. L. Freedman *et al.* [HST Collaboration], *Astrophys. J. 553:47, 2001*

Astro/Cosmo Evidences of DM

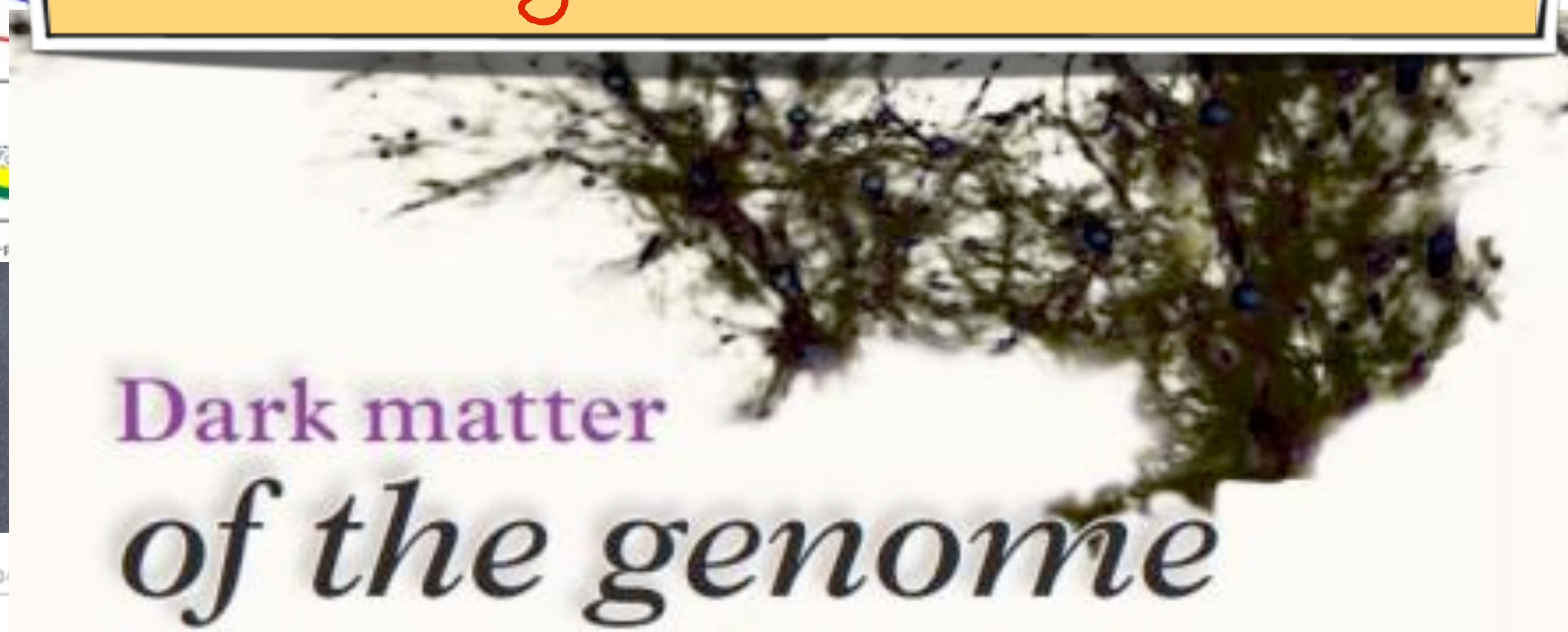


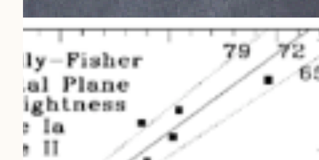


B. D. Fields and

VMAP Science Team

Not the only Dark Matter around...





"The genomes of multicellular animals are big and complex, but functions have been defined for only a small proportion of them. Only 1% of the human genome is transcribed into protein-coding messenger RNA (mRNA) and non-protein-coding RNA (ncRNA), and DNA elements that control the expression of genes occupy another ~0.5%, suggesting that the remaining "dark genome" is nonfunctional padding."

M. Blaxter, "Revealing the Dark Matter of the Genome", Science 330, 1758, 2010

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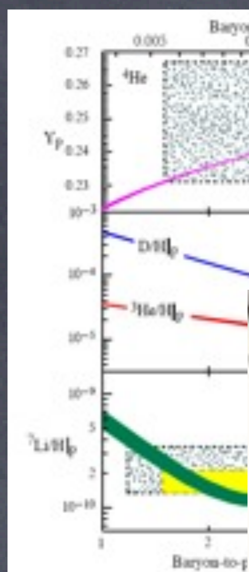
Astro/Cosmo Evidences of DM



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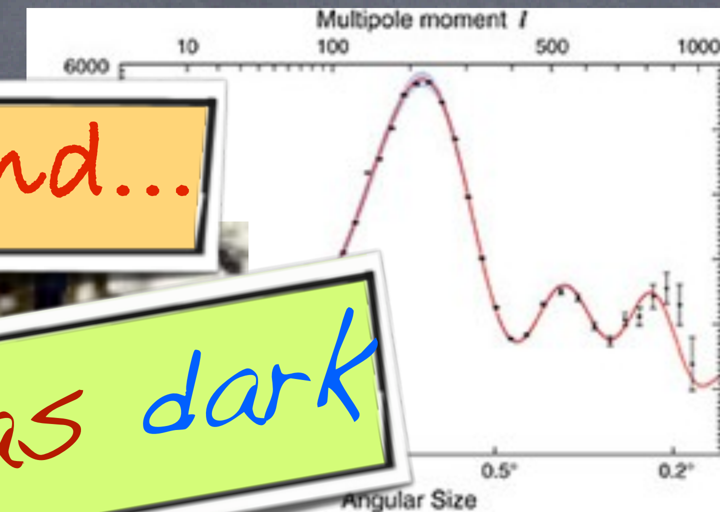
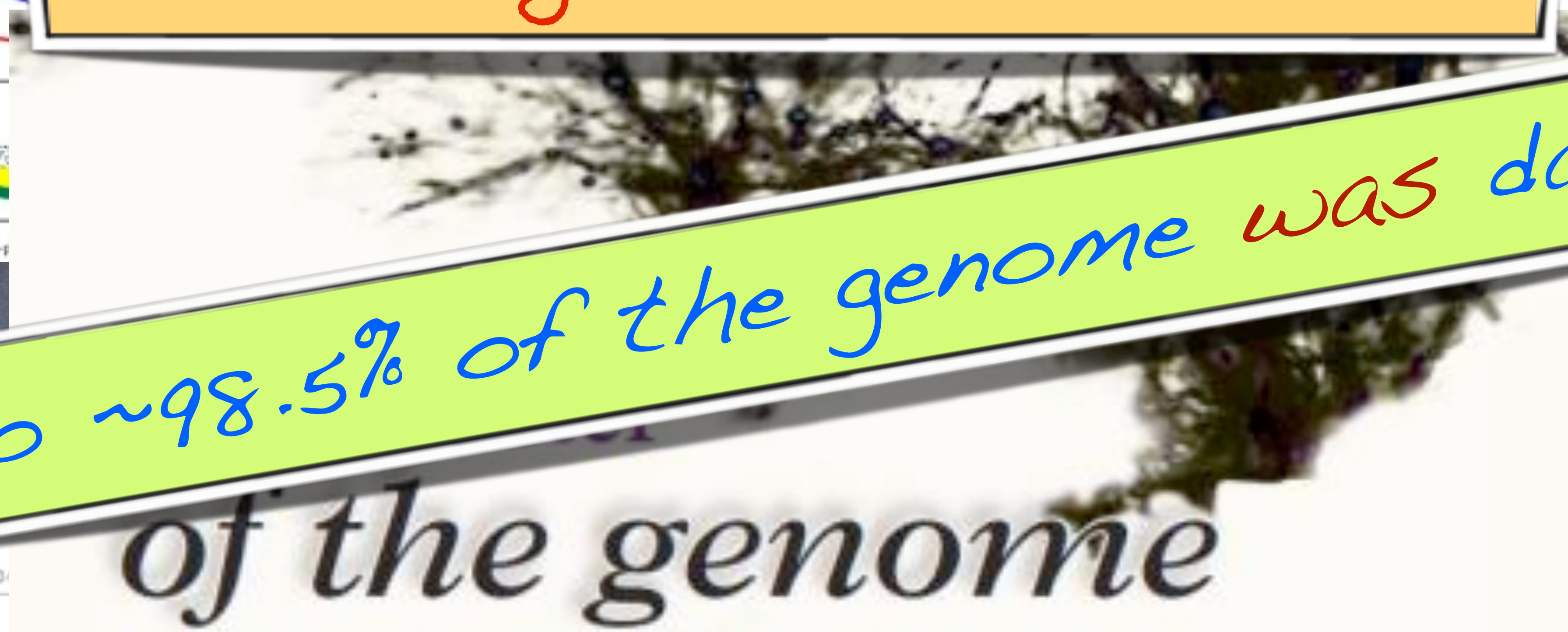
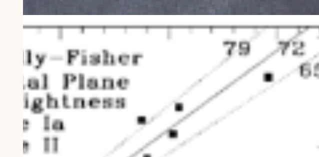


WMAP Science Team

Not the only Dark Matter around...



So ~98.5% of the genome was dark



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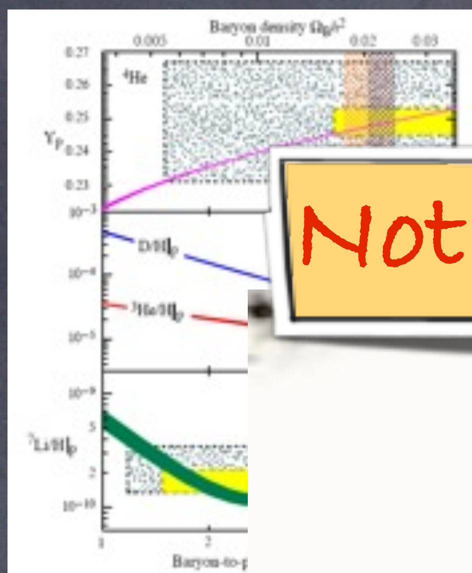
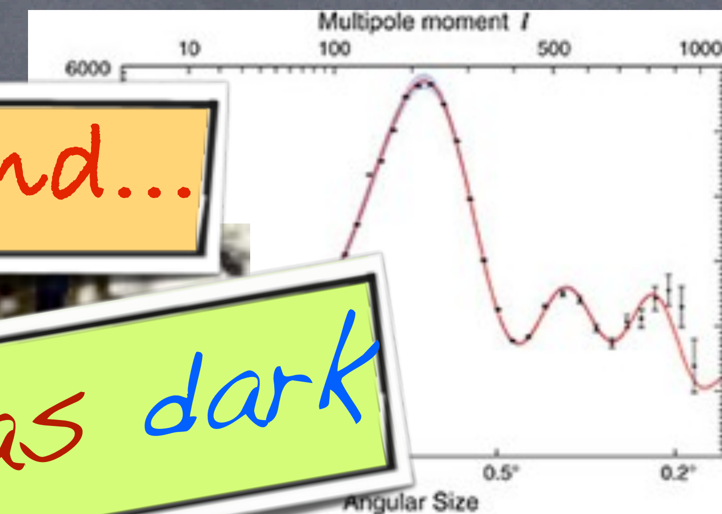
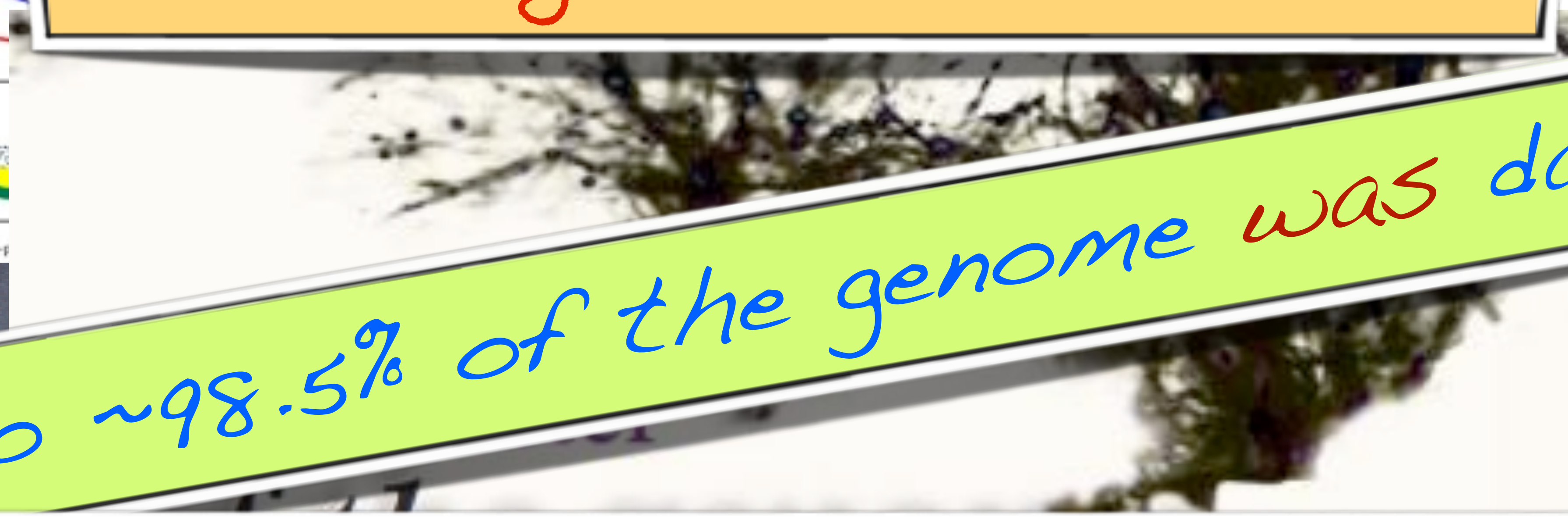






B. D. Fields and

WMAP Science Team

Not the only Dark Matter around...

So ~98.5% of the genome was dark

"The Encyclopedia of DNA Elements (ENCODE) project has systematically mapped regions of transcription, transcription factor association, chromatin structure and histone modification. These data enabled us to assign biochemical functions for 80% of the genome, in particular outside of the well-studied protein-coding regions."

The ENCODE Project Consortium, "An integrated encyclopedia of DNA elements in the human genome", Nature 489, 58, 2012

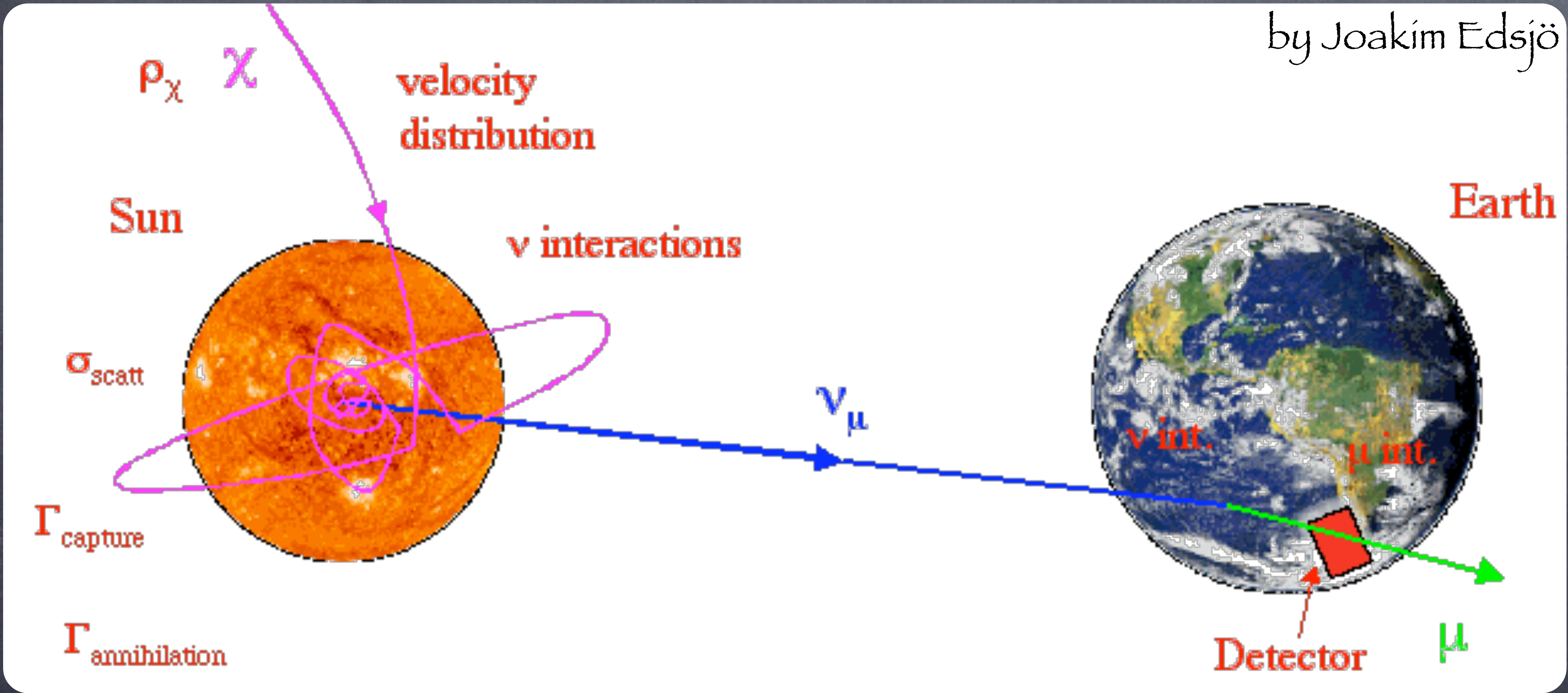
+ 29 more articles on September 6, 2012

n],

Detecting Dark Matter

- Collider Searches
  - Missing Energy (Tevatron, LHC, ILC?)
- Direct Detection
  - Nuclear Recoil produced by DM scattering (CDMS, CRESST, XENON, DAMA/LIBRA, KIMS, CoGeNT, COUPP...)
- Indirect Detection
  - Observation of annihilation/decay products
    - Gamma-ray telescopes (Fermi-LAT, MAGIC, VERITAS, HESS, CANGAROO-III, EGRET...)
    - Antimatter experiments (PAMELA, HEAT, BESS...)
    - Neutrino detectors/telescopes (IceCUBE, ANTARES, AMANDA, Super-Kamiokande...)

Neutrinos from DM annihilation in the Sun



Neutrinos from DM annihilation in the Sun

- WIMPs elastically scatter with the nuclei of the Sun to a velocity smaller than the escape velocity, so they remain trapped inside

  Additional scattering give rise to an isothermal distribution

$$C_{\odot} \simeq 9 \times 10^{23}\,\mathrm{s}^{-1} \left(\frac{\rho_0}{0.3\ \mathrm{GeV/cm}^3} \right) \left(\frac{270\ \mathrm{km/s}}{\bar{v}_{local}} \right)^3 \left(\frac{\sigma_{SD}}{10^{-3}\ \mathrm{pb}} \right) \left(\frac{50\ \mathrm{GeV}}{m_\chi} \right)^2$$

- Trapped WIMPs can annihilate into SM particles

- After some time, annihilation and capture rates equilibrate

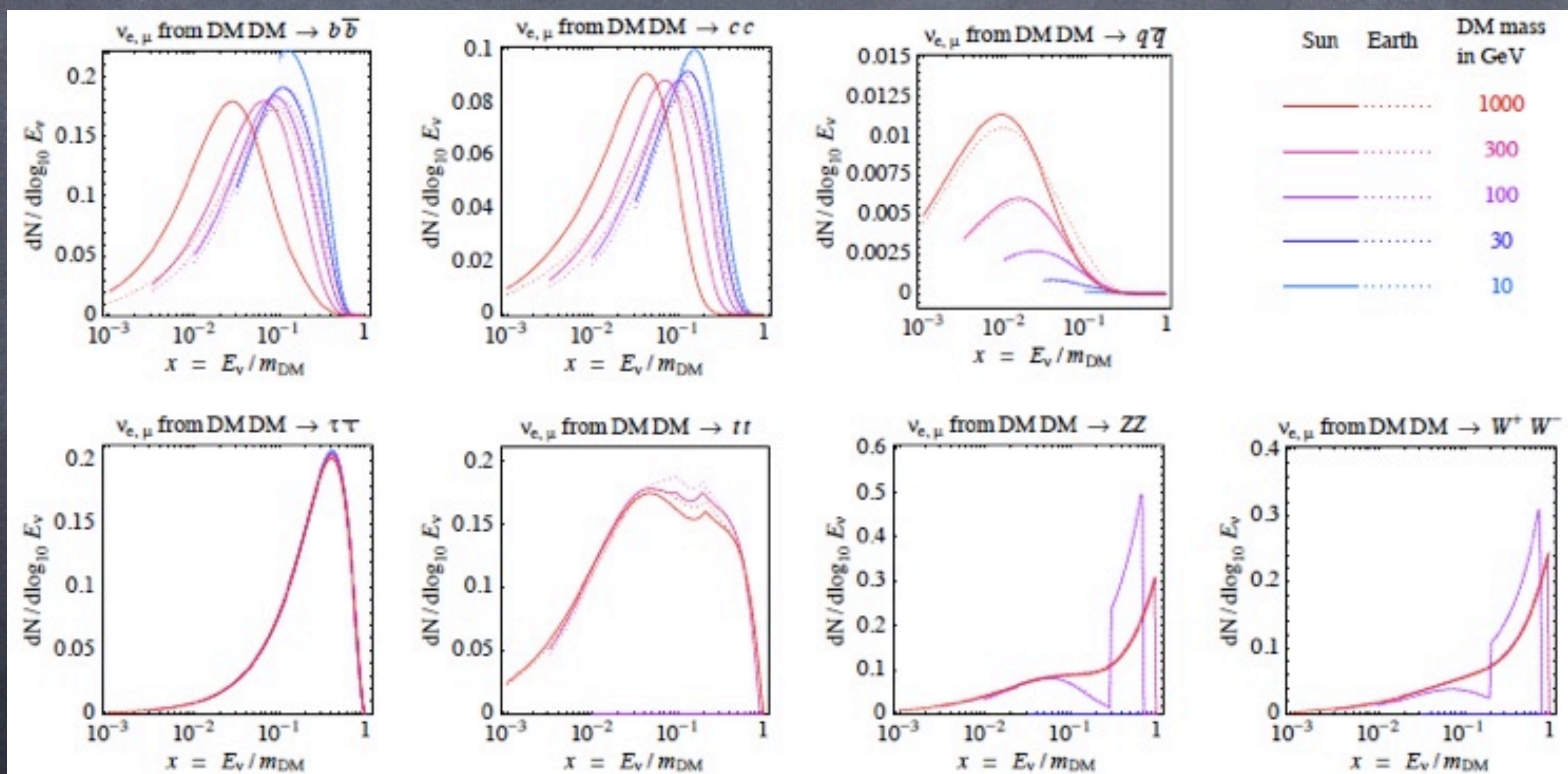
$$\Gamma_{ann} \simeq \frac{1}{2} C_{\odot} \tanh^2 \left(\frac{t_{\odot}}{t_{eq}} \right)$$

- Only neutrinos can escape

- Only annhilations into quarks, gauge bosons and tau leptons had been considered so far

- Annihilations into muons and electrons/positrons do not produce high-energy neutrinos

- Annihilations into light quarks only produce significant amounts of high-energy neutrinos at the low-energy tail (GeV) of the spectrum



M. Cirelli, N. Fornengo, T. Montaruli, I. Sokalski, A. Strumia and F. Vissani, *Nucl. Phys. B727:99, 2005*

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

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

Why not annihilations into light quarks, muons or electrons?

- Electrons/positrons do not produce neutrinos...

- Muons lose energy electroma... cay at rest

$\left(\frac{}{10 \text{ GeV}}\right) s$

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

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

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

Novel test: disregarded so far

Charged pions and kaons will scatter in the dense interior ($\sim 10^2$ g cm^{-3}) of the Sun and thermalize, yielding ultimately mostly thermal photons and low-energy neutrinos typical of meson decay or capture at rest ($\sim$30 MeV for pions and muons and $\sim$230 MeV for kaons). Such low-energy neutrinos have cross sections too small to produce measurable interaction rates in present detectors for the annihilation rates of interest. For several of the WIMP's

T. K. Gaisser, G. Steigman and S. Tilav, *Phys. Rev. D34:2206, 1986*

With relatively low energies and numbers, the neutrinos derived from muon or light hadron decays are unobservable.

S. Ritz and D. Seckel, *Nucl. Phys. B304:877, 1988*

particles (lighter quarks, electrons, and muons do not contribute significantly to the neutrino flux). For the Higgs

L. Bergström, J. Edsjö and P. Gondolo, *Phys. Rev. D55:1765, 1997*

In addition to energy losses, we should also take into account that interaction of hadrons with the medium could lead to the production of additional hadrons. For instance, a heavy-hadron collision with the medium may produce additional light hadrons. However these additional light hadrons of lower energies are easily stopped, as discussed before, and therefore give a negligible contribution to the neutrino flux in our relevant energy range from this process. We therefore ignore here this possibility, a consistent assumption under our approximations.

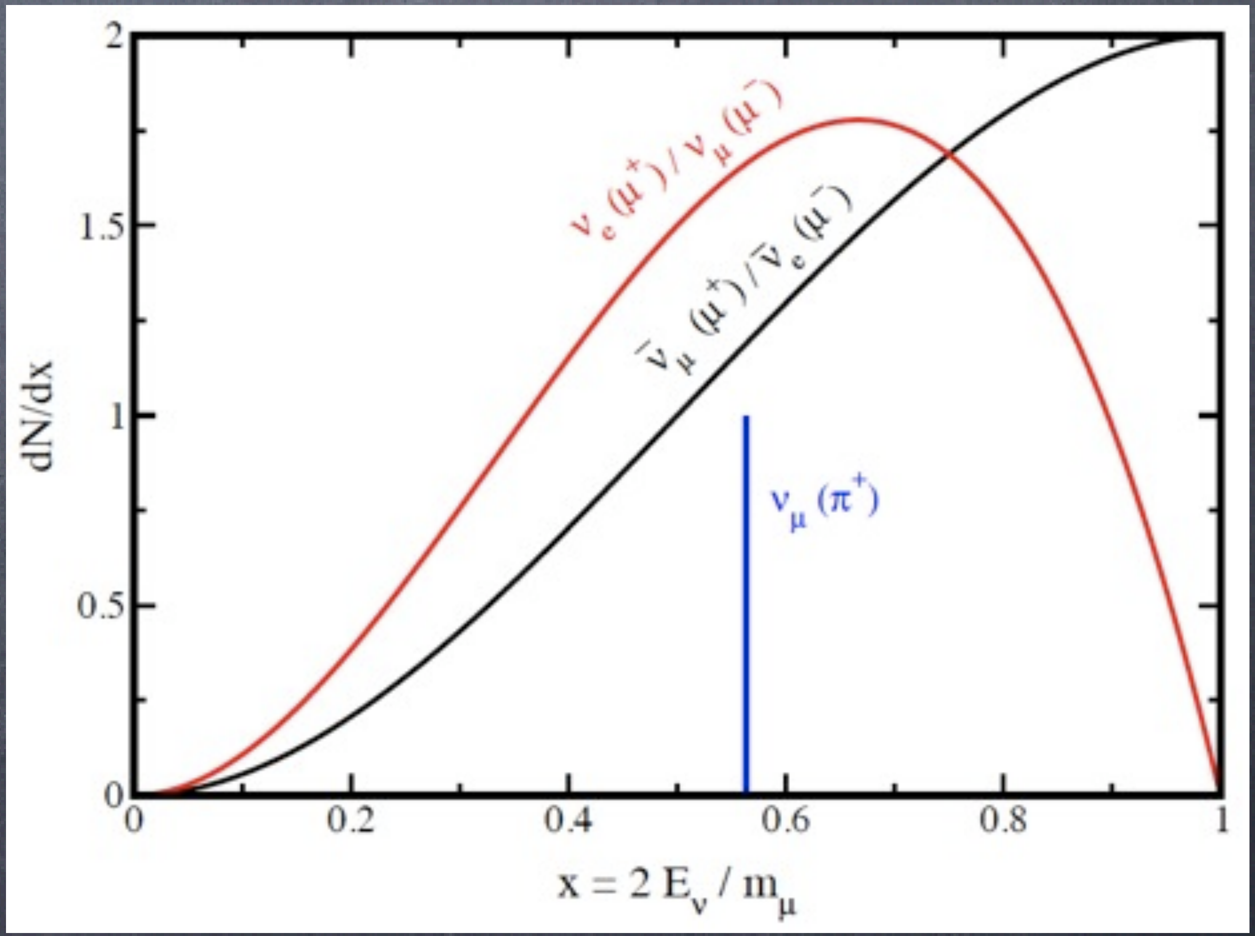
M. Cirelli, N. Fornengo, T. Montaruli, I. Sokalski, A. Strumia and F. Vissani, *Nucl. Phys. B727:99, 2005*

- 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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



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

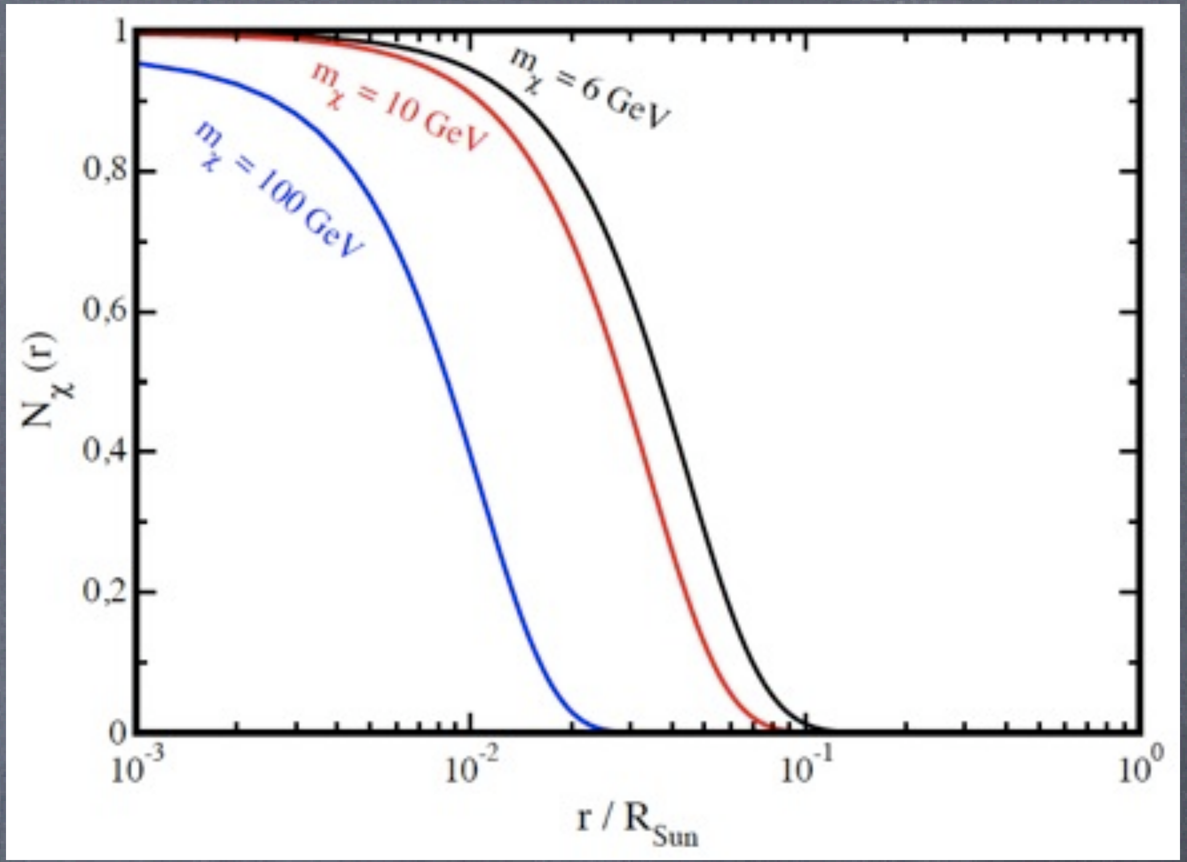
- Finally, we count the number of pions and muons (of each charge) that decay at rest

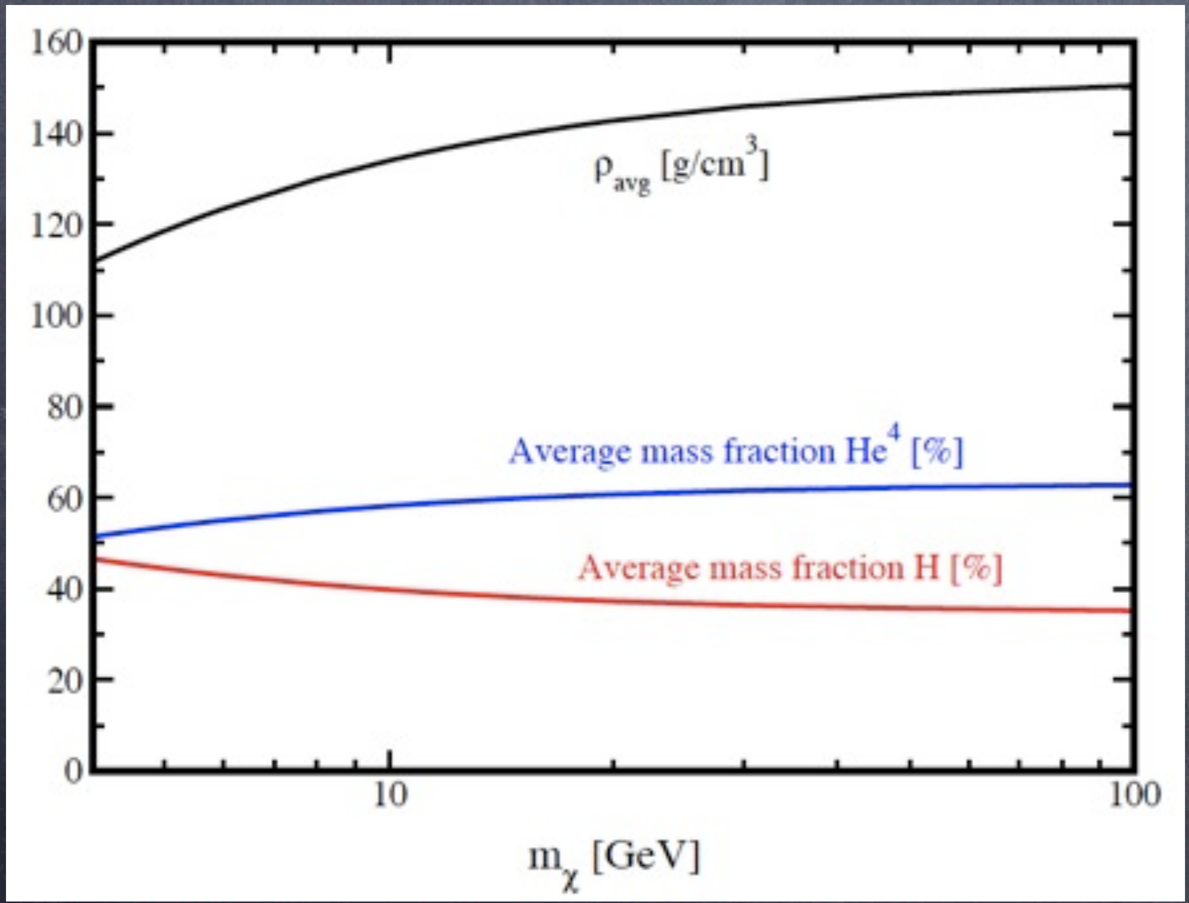
Distribution of WIMPs in the Sun

Isothermal distribution:

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

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





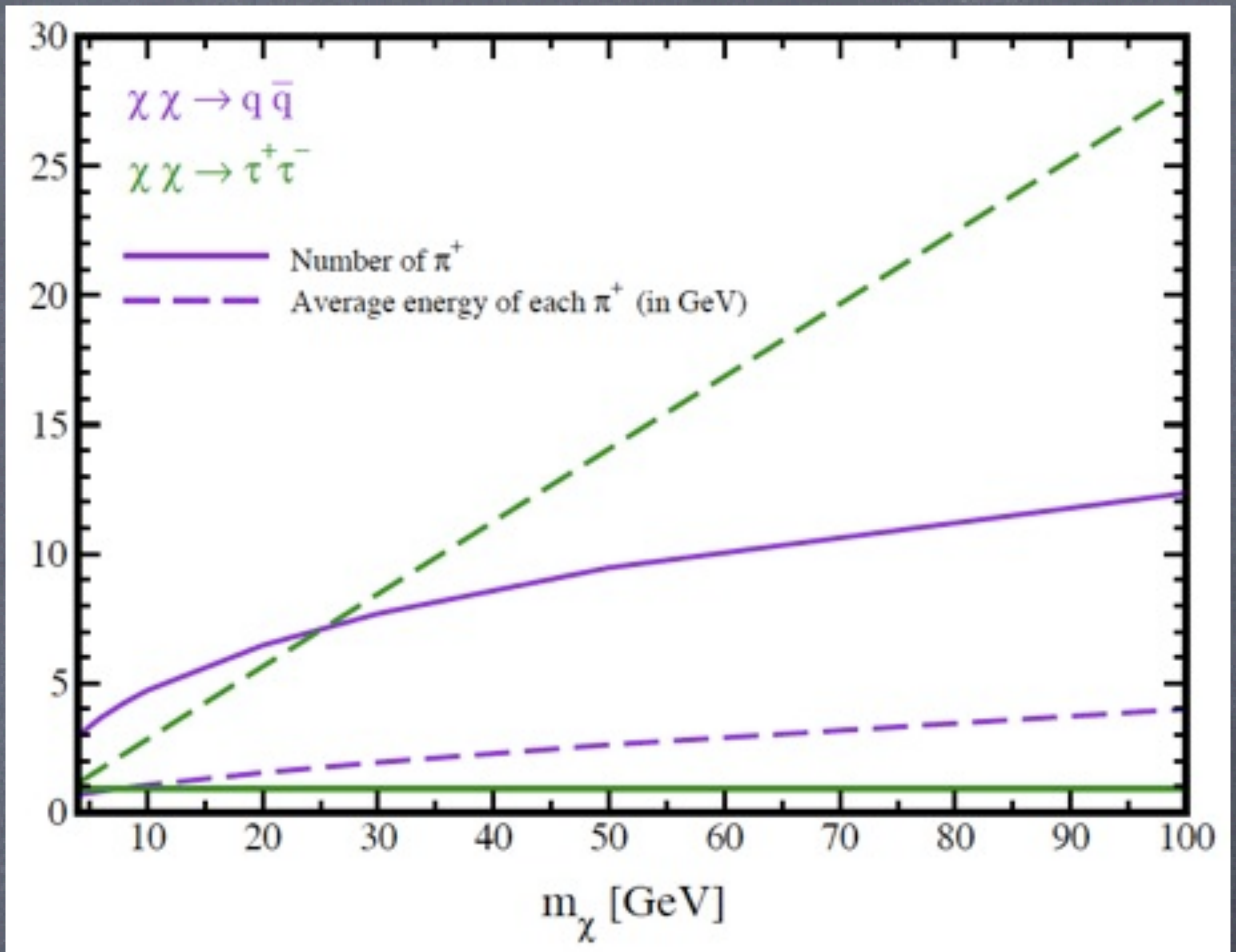
Average density and composition:

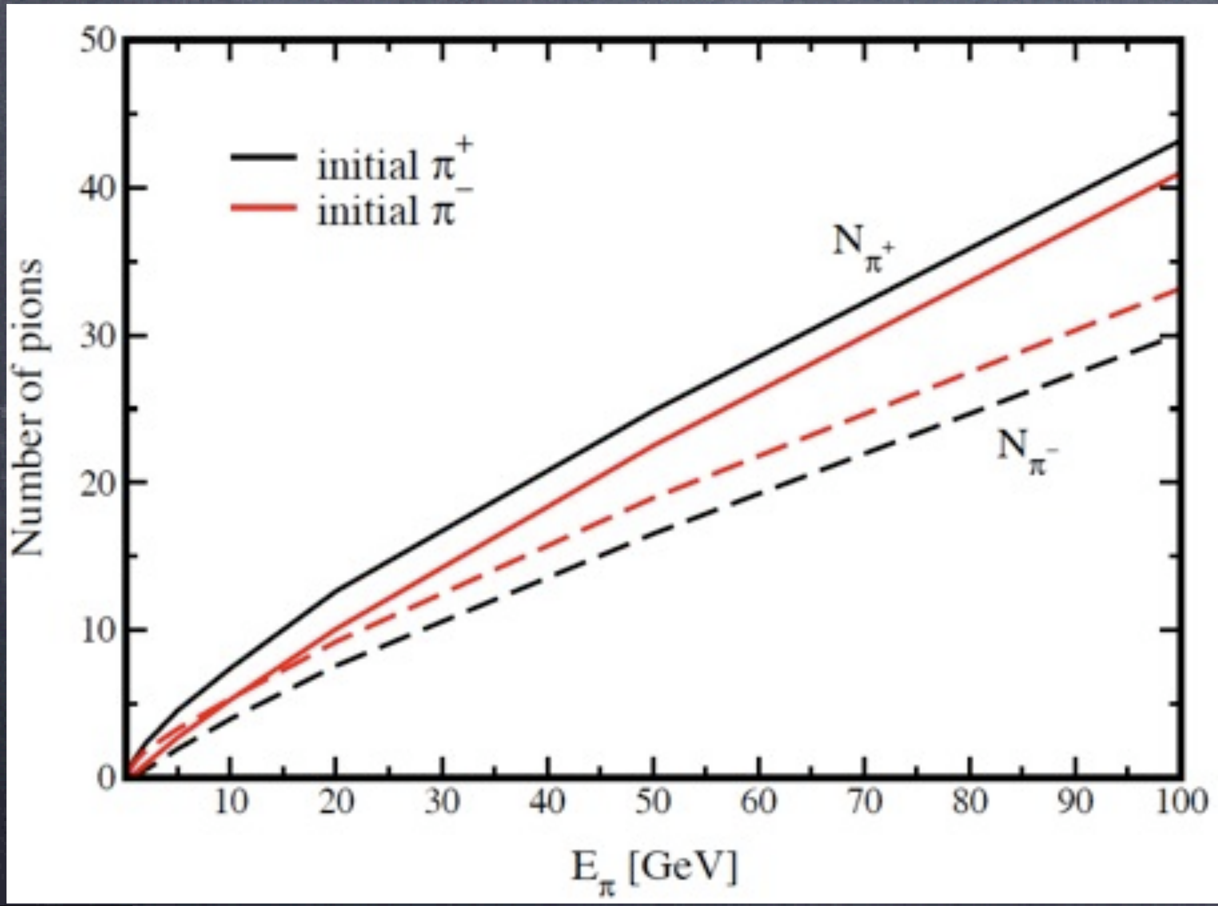
Only shown the two main elements, although we take 29 in our computations

From
A. M. Serenelli, W. C. Haxton and C. Peña-Garay, *Astrophys. J. 743:24, 2011*

Pions production in the Sun

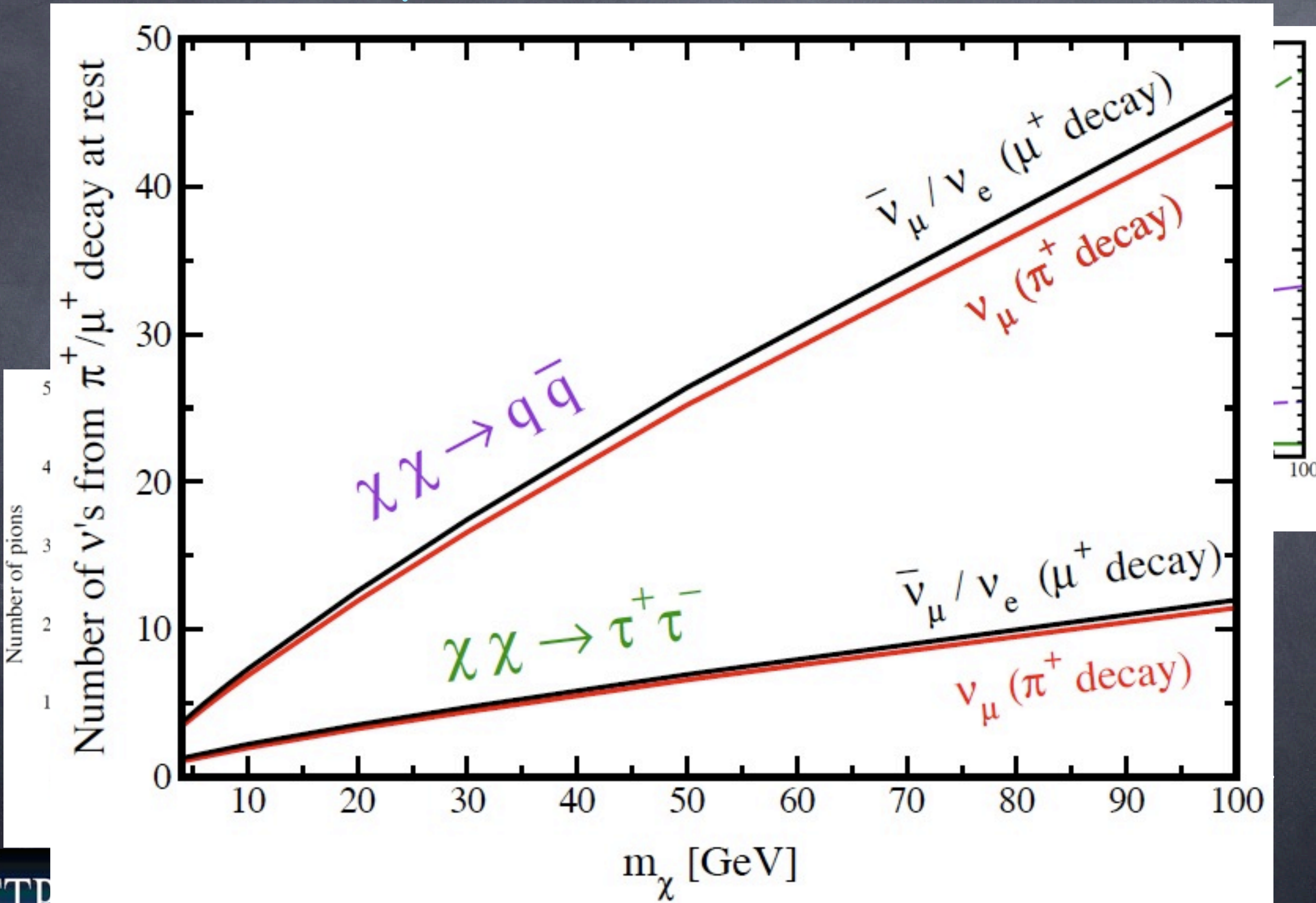
(Approximate) Number of pions and average energy just after WIMPs annihilations





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

Pions production in the Sun



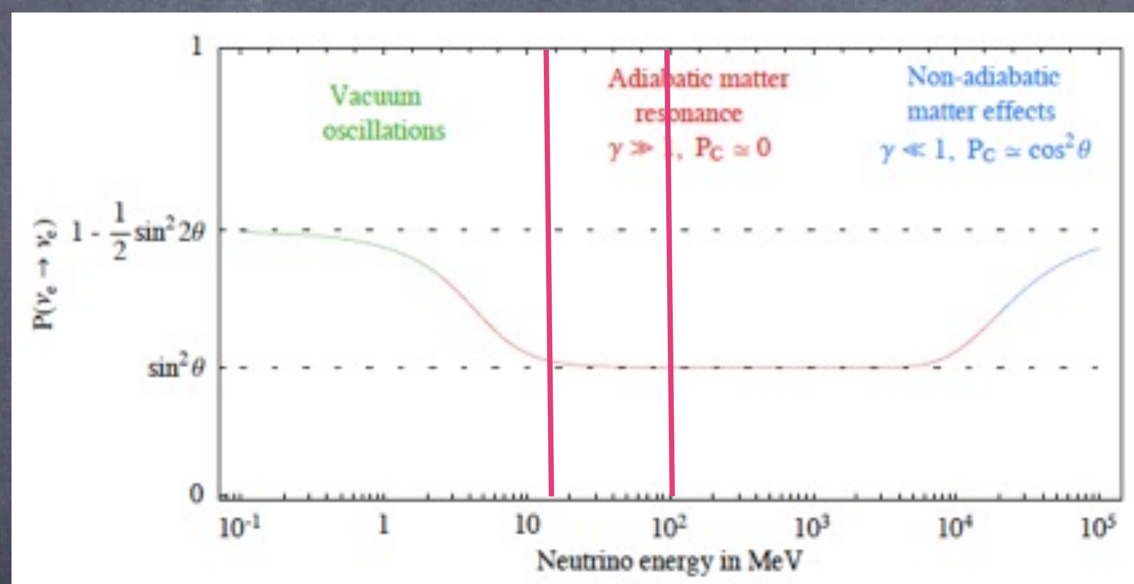
Neutrino propagation through the Sun

Matter effects dominate:

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta \mp 2\sqrt{2} G_F N_e E} \longrightarrow \begin{array}{ll} \cos 2\theta_m \simeq -1 & \text{neutrinos} \\ \cos 2\theta_m \simeq +1 & \text{antineutrinos} \end{array}$$

The propagation is adiabatic:

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



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

Probabilities at detection

(neglecting the small Earth-matter effect)

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

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

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

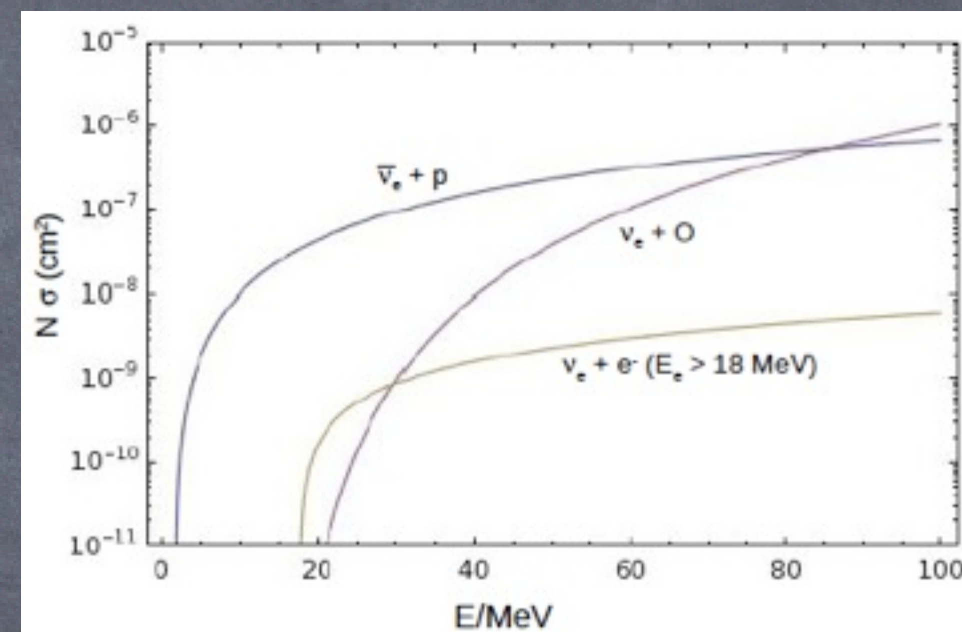
$$P(\nu_e \to \nu_e) = \sin^2\theta_{12} \cos^2\theta_{13} + \sin^4\theta_{13} \simeq 0.304$$

Detection of MeV neutrinos with SK

Super-Kamiokande:
Water-Cherenkov detector with a fiducial volume of 22.5 ktons

Main signature of MeV neutrinos: inverse-beta decay

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



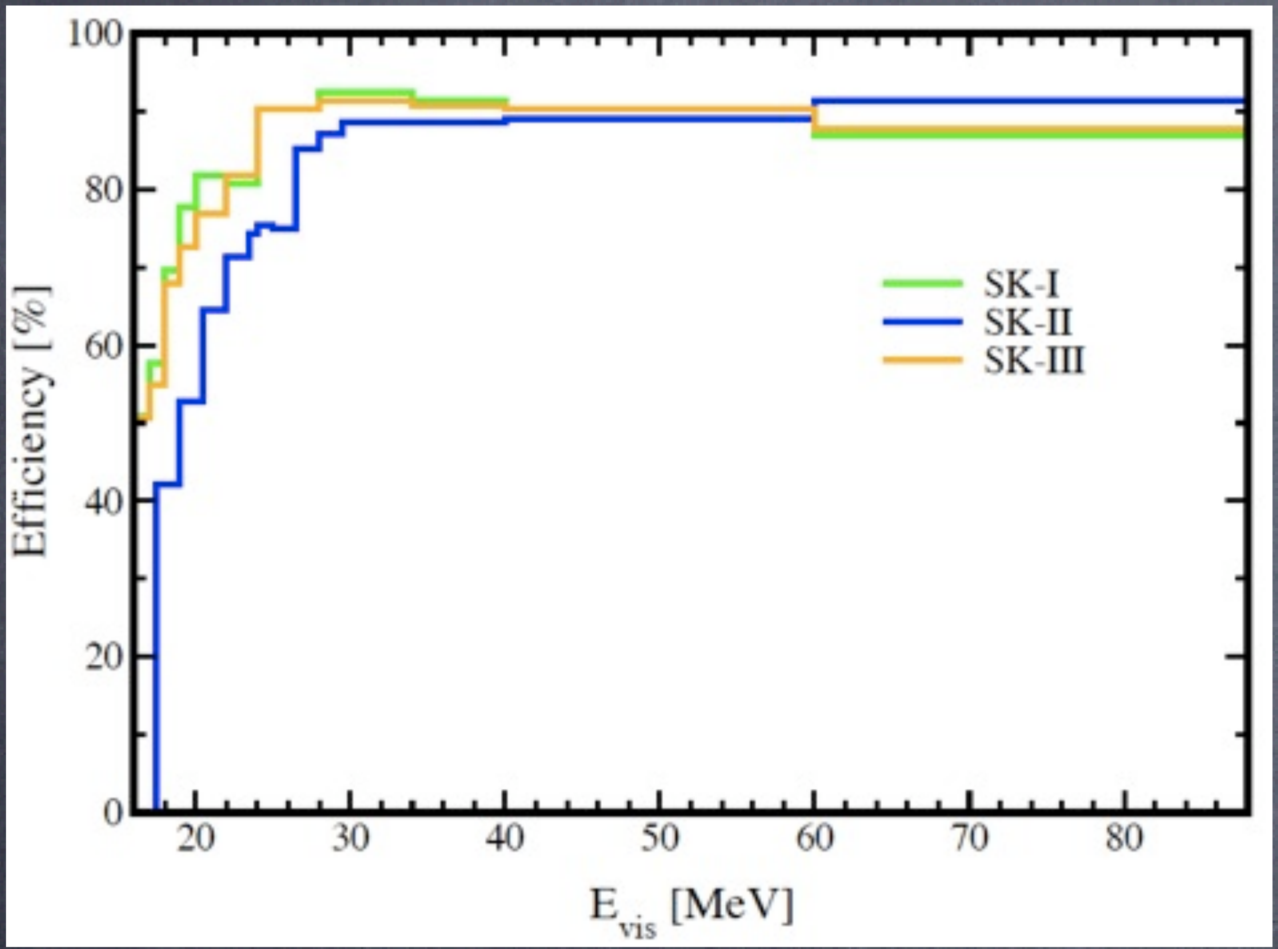
C. Lunardini and O. L. G. Peres, *JCAP 0808:033, 2008*

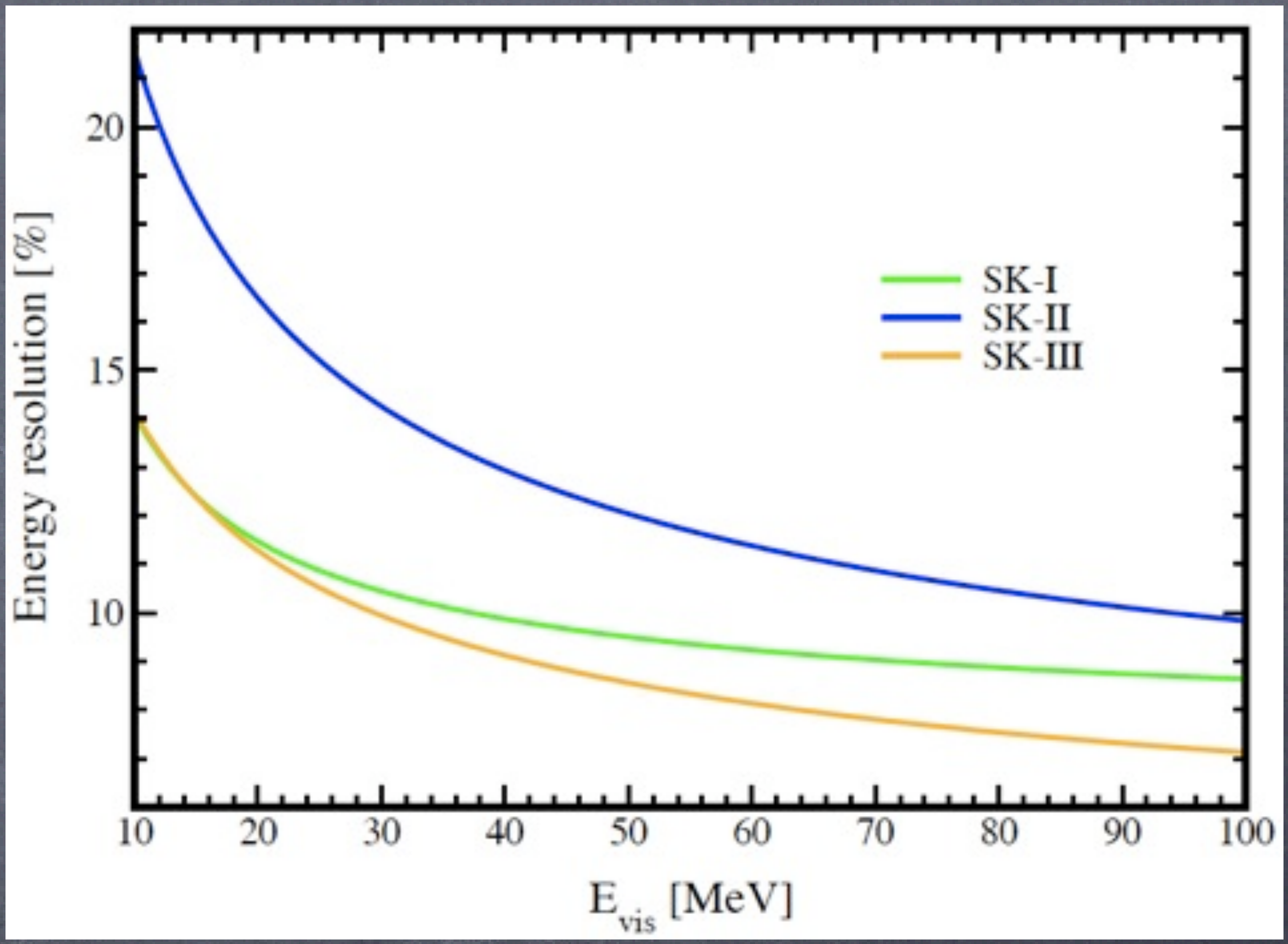
We consider inverse-beta decay off free protons (antineutrinos), with the full differential cross section and interactions off bound nucleons (neutrinos and antineutrinos), by implementing a relativistic Fermi gas model

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*

18 4-MeV bins [16,88] MeV for SK-I and SK-III
Same for SK-II, but the first bin is [17.5,20] MeV





Produced with data from:

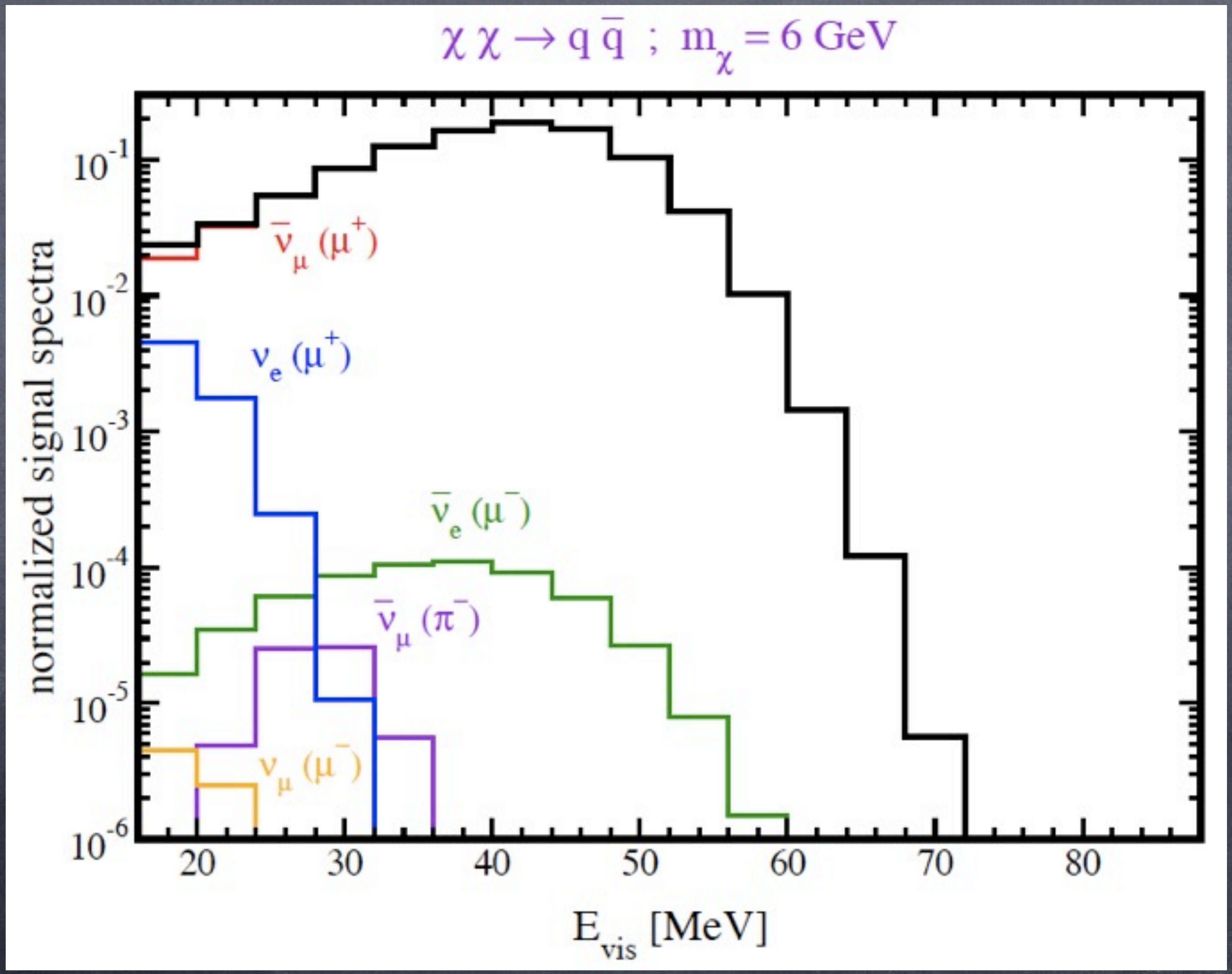
K. Bays *et al.* [Super-Kamiokande Collaboration], *Phys. Rev. D85:052007, 2012*
K. Bays, private communication

Produced with data from:

J. Hosaka *et al.* [Super-Kamiokande Collaboration], *Phys. Rev. D73:112001, 2006*
J. P. Cravens *et al.* [Super-Kamiokande Collaboration], *Phys. Rev. D78:032002, 2008*
K. Abe *et al.* [Super-Kamiokande Collaboration], *Phys. Rev. D83:052010, 2011*

Spectrum of the potential signal at SK-I

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



Two main backgrounds

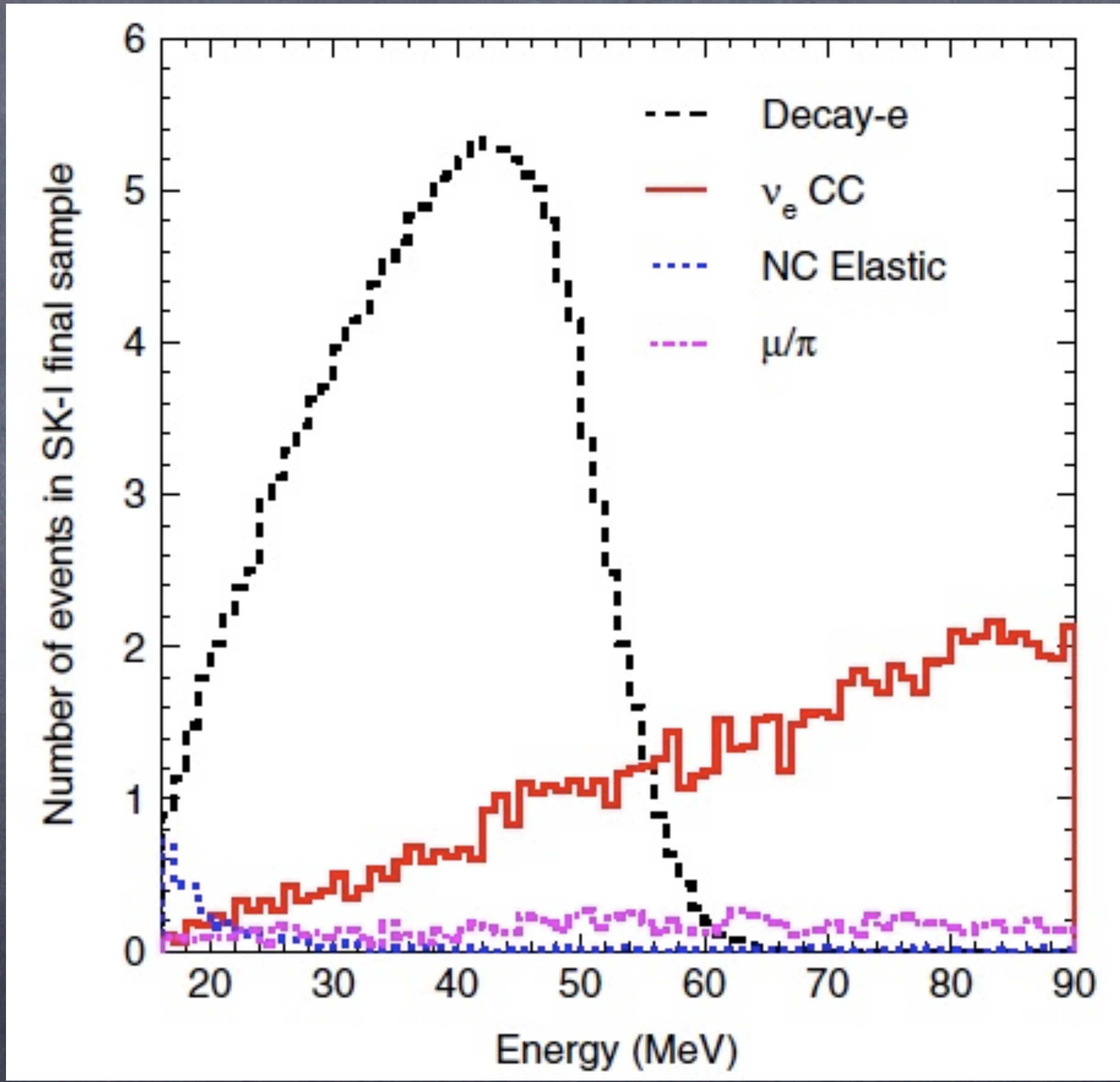
- Invisible muons: Michel positrons/electrons from the decays at rest of low-energy muons, produced by atmospheric muon neutrinos with energies up to about 400 MeV, which are below detection threshold (E < 160 MeV)

- Atmospheric electron neutrinos with energies up to about 350 MeV

Two subdominant backgrounds
(not included in our analysis)

- Atmospheric neutrino neutral current elastic events

- muon/pion production from atmospheric neutrinos: pions and muons slightly above threshold misidentified as electrons



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

Statistical analysis

Unbinned maximum likelihood fit (as SK): for each phase

number of bins

WIMP signal

atmospheric ν_e bkg

$$L = e^{-(\alpha+\beta+\gamma)} \prod_{l=1}^{18} \left[(\alpha \cdot A_l) + (\beta \cdot B_l) + (\gamma \cdot C_l) \right]^{N_l}$$

parameters to fit: total number of events

invisible muons bkg

number of detected events in bin l

Statistical analysis

Unbinned maximum likelihood fit (as SK): for each phase

number of bins — WIMP signal — atmospheric ν_e bkg

$$L = e^{-(\alpha+\beta+\gamma)} \prod_{l=1}^{18} \left[(\alpha \cdot A_l) + (\beta \cdot B_l) + (\gamma \cdot C_l) \right]^{N_l}$$

parameters to fit: total number of events — invisible muons bkg — number of detected events in bin l

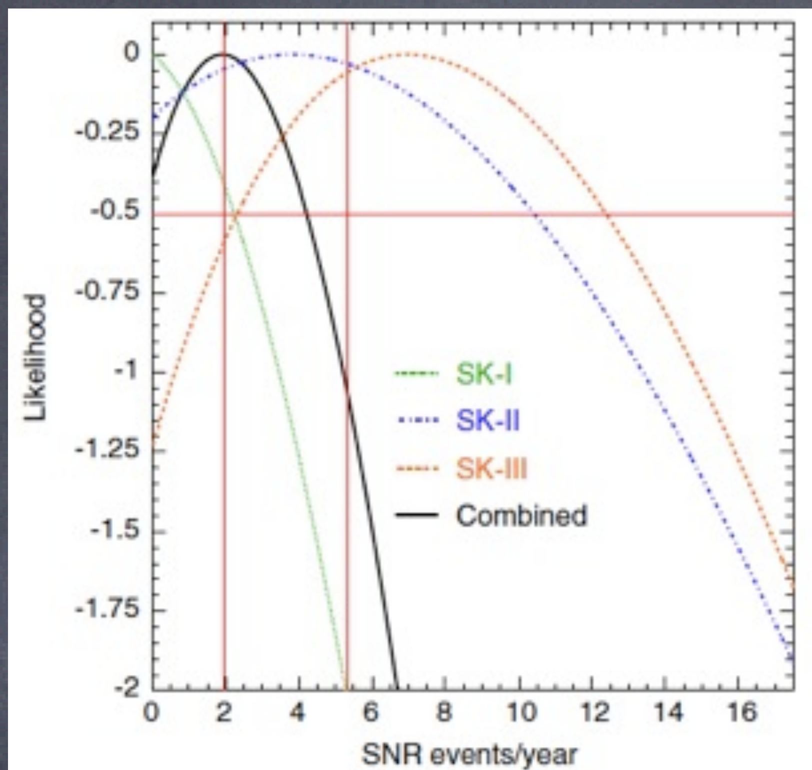
Energy-independent efficiency systematic error

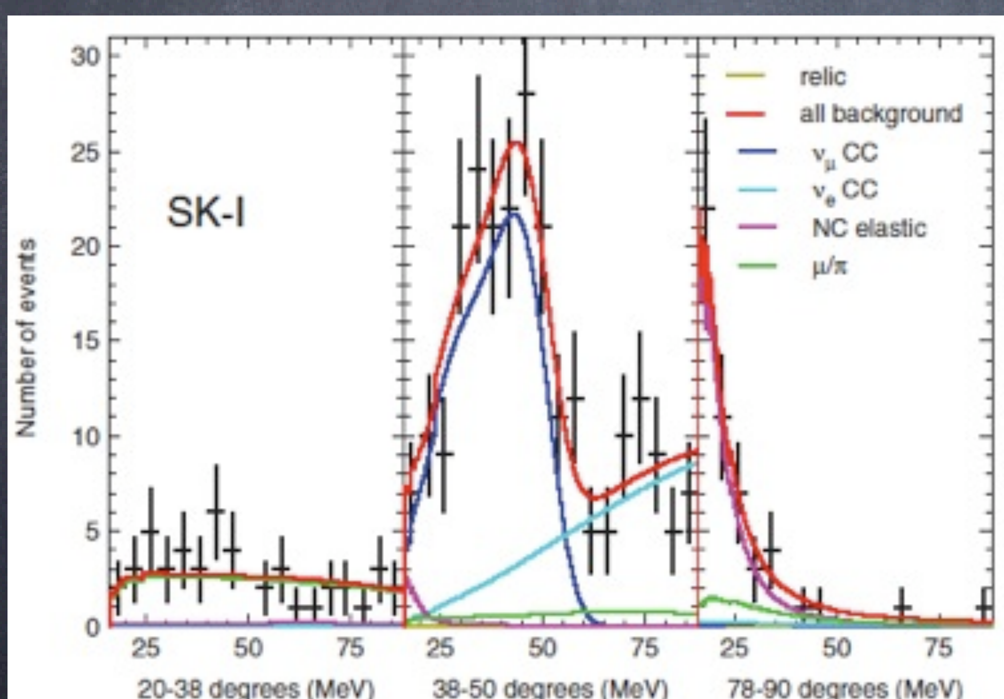
Error source	SK-I	SK-II	SK-III
Cut reduction	3.1%	4.4%	3.1%
Fiducial volume	1.3%	1.1%	1.0%
Cross section	1.0%	1.0%	1.0%
Live time	0.1%	0.1%	0.1%
Total	3.51%	4.65%	3.41%

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

$$L_{sys}(\alpha) = \int_0^1 L(\varepsilon\alpha) \cdot P(\varepsilon) \cdot \varepsilon \cdot d\varepsilon$$

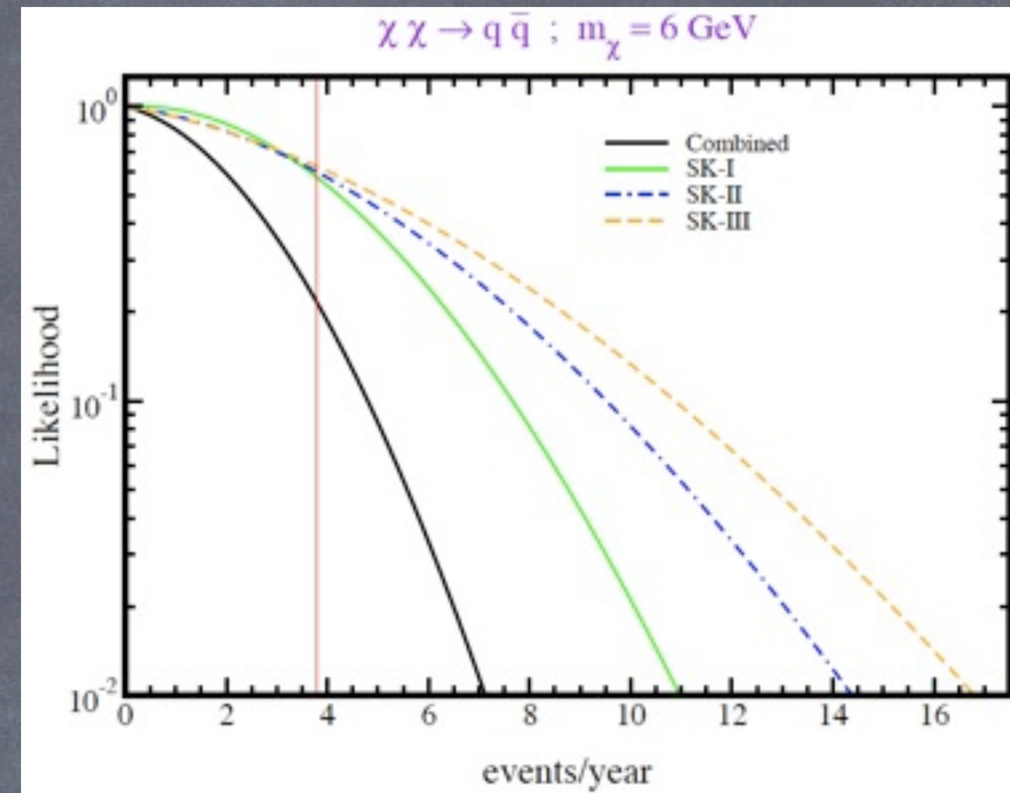
Diffuse Supernova Neutrino Background search

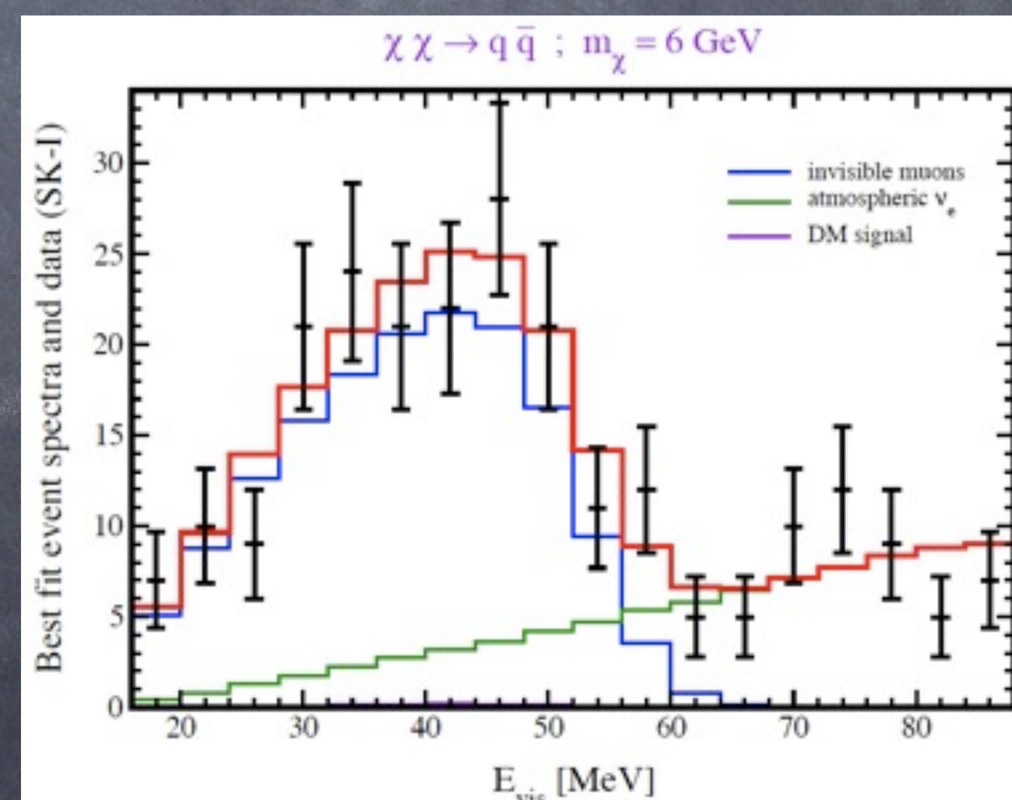




K. Bays *et al.* [Super-Kamiokande Collaboration], *Phys. Rev. D85:052007, 2012*

WIMPs annihilations in the Sun





Obtaining the 90% CL bound

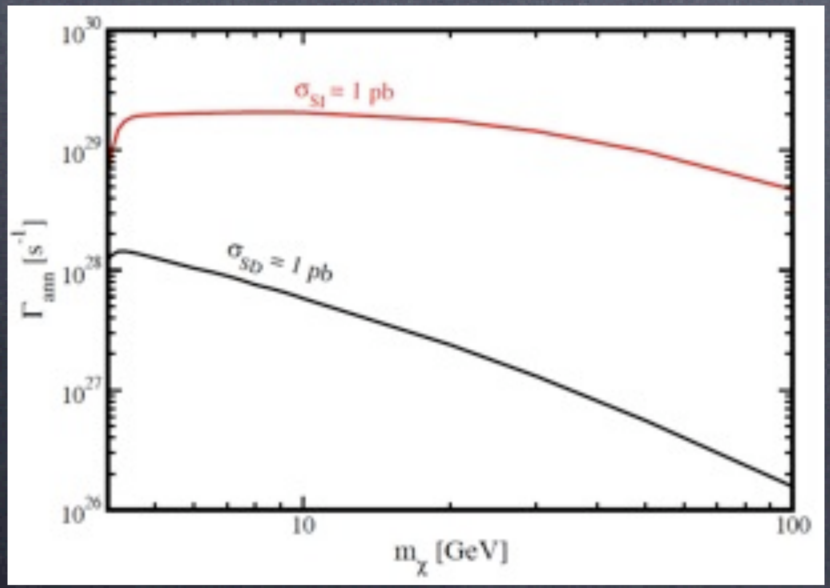
Combined likelihood: $L_{tot}(\bar{\alpha}) = L^{\max}_{SK-I}(\bar{\alpha}) \times L^{\max}_{SK-II}(\bar{\alpha}) \times L^{\max}_{SK-III}(\bar{\alpha})$

90% CL limit on the number of signal events/year, $\bar{\alpha}_{90}$:

$$\frac{\int_0^{\bar{\alpha}_{90}} L_{tot}(\bar{\alpha})\, d\bar{\alpha}}{\int_0^{\infty} L_{tot}(\bar{\alpha})\, d\bar{\alpha}} = 0.90$$

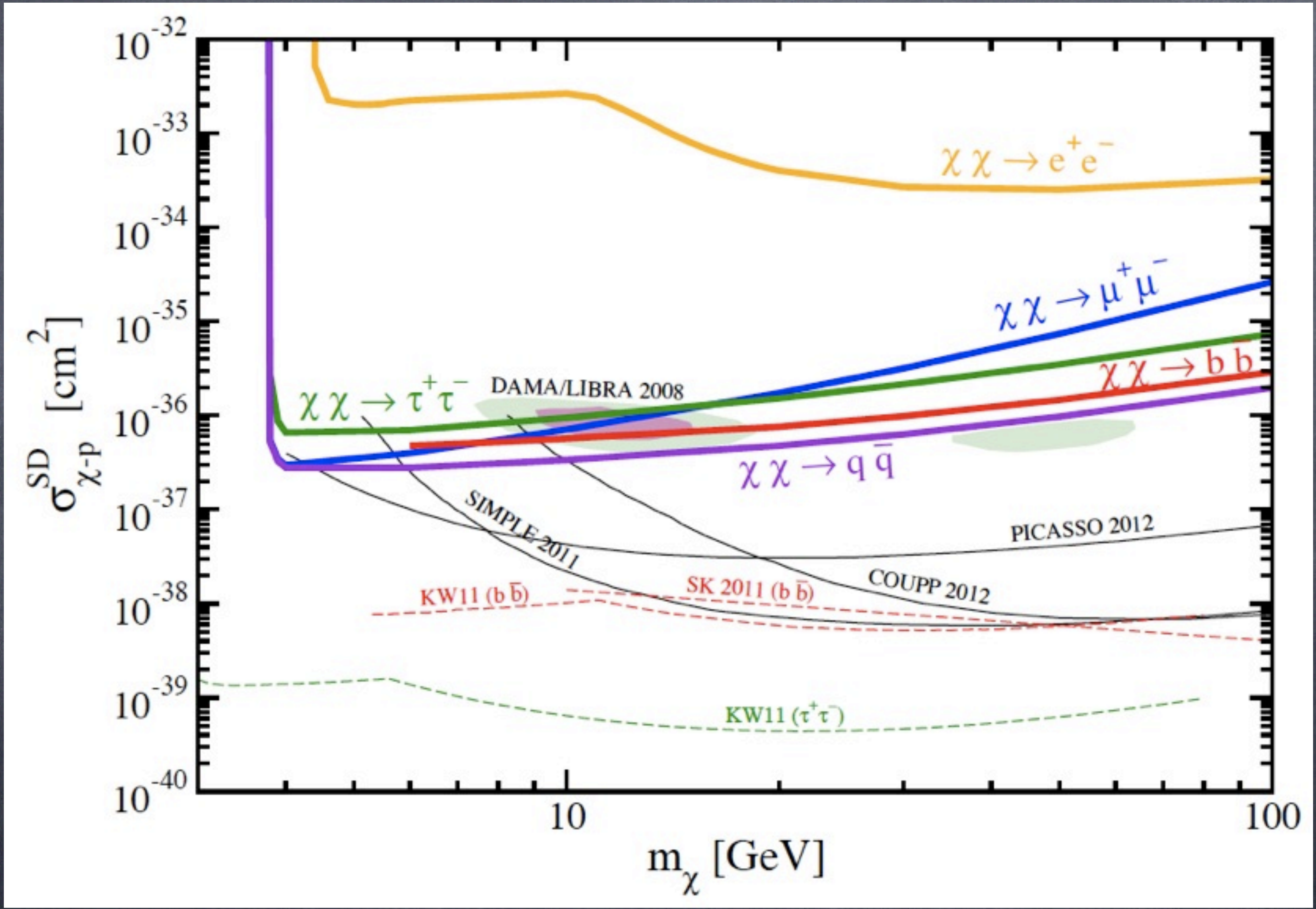
90% CL limit on the scattering cross section, σ_χ^{90} :

$$\Gamma_{ann}(m_\chi, \sigma_\chi^{90}) \frac{\sum_{SK} A^{SK} t_{SK}}{\sum_{SK} t_{SK}} = \bar{\alpha}_{90}$$



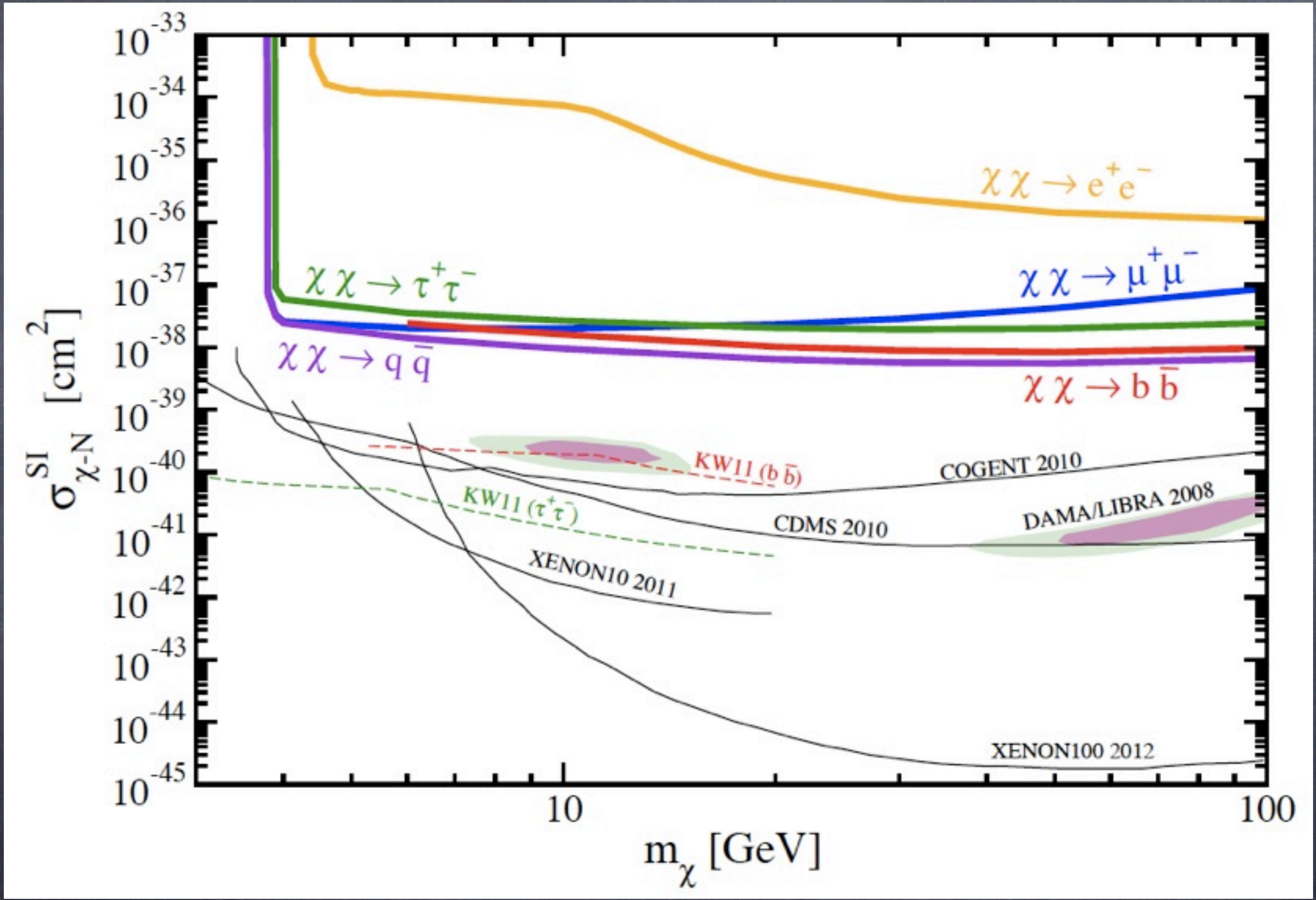
number of signal events/annihilation for each SK phase

Limits on the SD scattering cross section



N. Bernal, J. Martín-Albo and SPR, *arXiv:1208.0834*

Limits on the SI scattering cross section



N. Bernal, J. Martín-Albo and SPR, *arXiv:1208.0834*

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 (see also arXiv:1208.0827)