Detecting DM with neutrino detectors

Fermilab

Batavia - 27 June 2008

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1 – Outline

Dark matter annihilations produce SM particles and eventually neutrinos, which can be detected and can provide information on the DM properties.

- Reconstructing WIMP properties with LBL neutrino oscillation detectors
- MeV dark matter and possible signals in SK and LENA
- Conclusions

1 – Outline

Strong evidence in favour of the existence of dark matter has been found from cosmological and astrophysical observations.

Its nature is still unknown but various candidates have been proposed, e.g.:

- **Weakly interacting massive particles (WIMP)**
- KeV sterile neutrinos
- **MeV particles** (scalars or fermions)
- superheavy relics

Here, I focus on WIMPs and MeV DM candidates and their indirect detection.

2 – Indirect detection

DM is copiously present in our galaxy and can accumulate in astrophysical objects.

If the density is sufficiently high, DM can self-annihilate and produce SM particle (photons, positrons, antiprotons, neutrinos) which can be detected.

- The flux of these products is proportional to the number of annihilations per unit time and volume:

$$\boxed{\text{flux} \propto \sigma v \frac{\rho^2(r)}{m_{\mathrm{DM}}^2}}$$

- Neutrinos are the end product of many annihilation channels.

3 – WIMPs

WIMPs (Weakly Interacting massive particle) are one of the favoured DM candidates. They have:

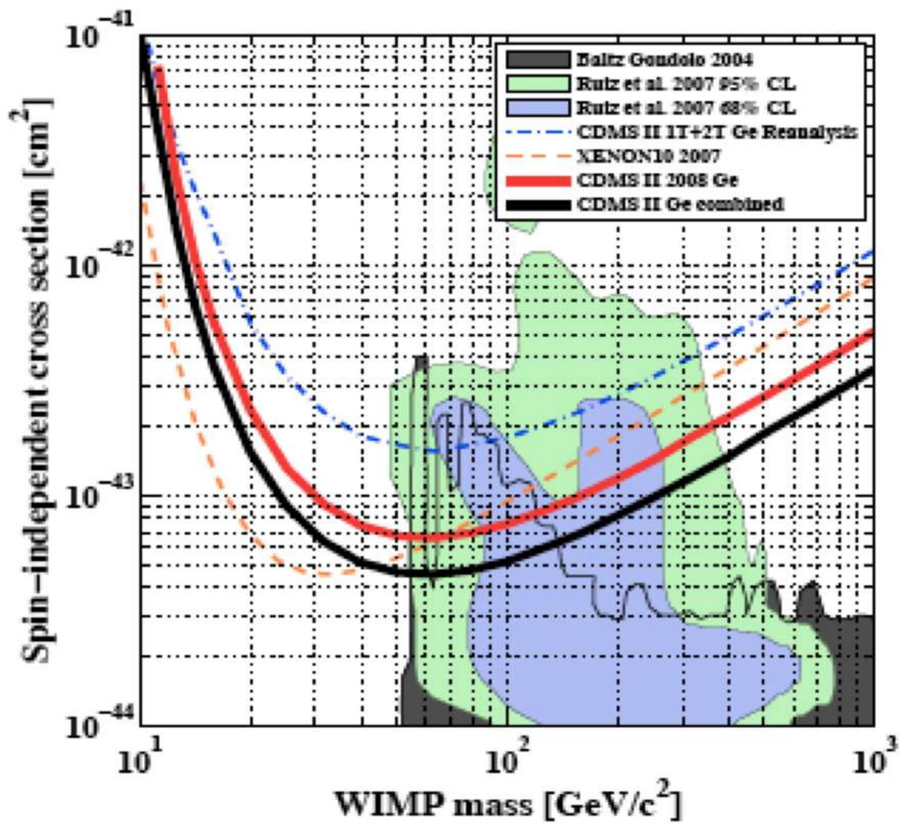
- Masses in the 10 GeV – 1 TeV range
- Interactions with weak cross sections

$$\boxed{\Omega_\chi h^2 = \frac{10^9}{M_{Pl}\ a}\frac{x_F}{\sqrt{g_*}} \simeq \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle}}$$

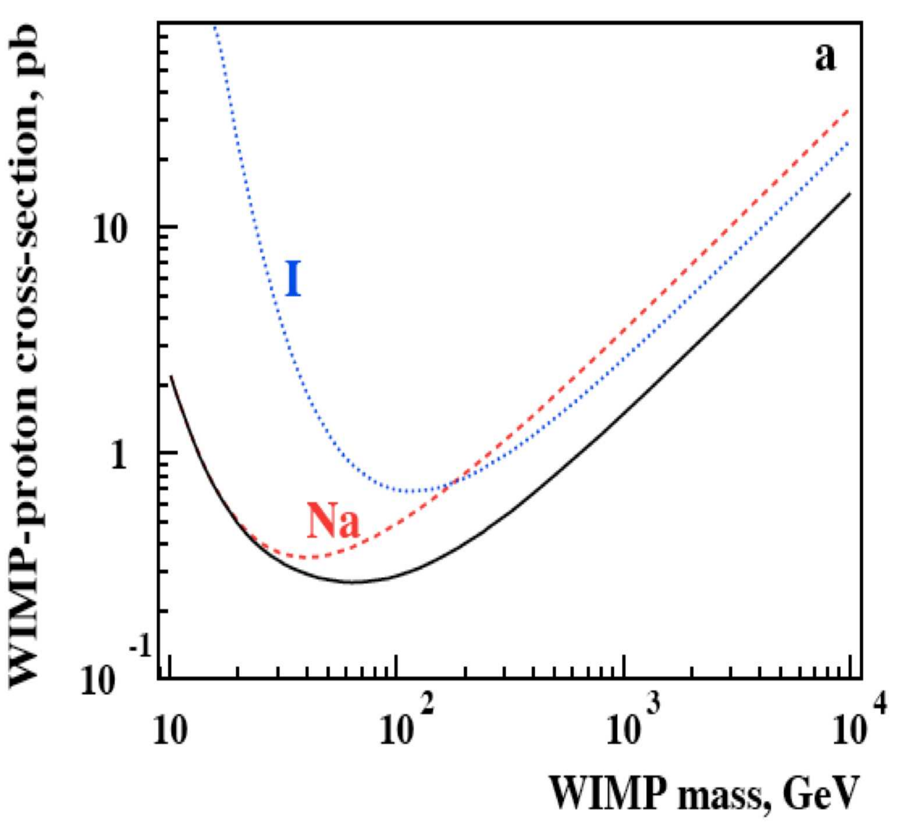
with $\langle \sigma v\rangle = a\ \mathrm{GeV}^{-2}$.

They can be embedded in extensions of the SM:
LSP in SUSY models (neutralinos);
lightest KK mode in extra-dimensions models;
stable fermions in Little Higgs models.

- **Direct detection**: a DM WIMP collides elastically with a nucleus in the detector, which recoils. Sensitivity to spin-dependent and spin-independent cross section.



[Ahmed et al., 2008]

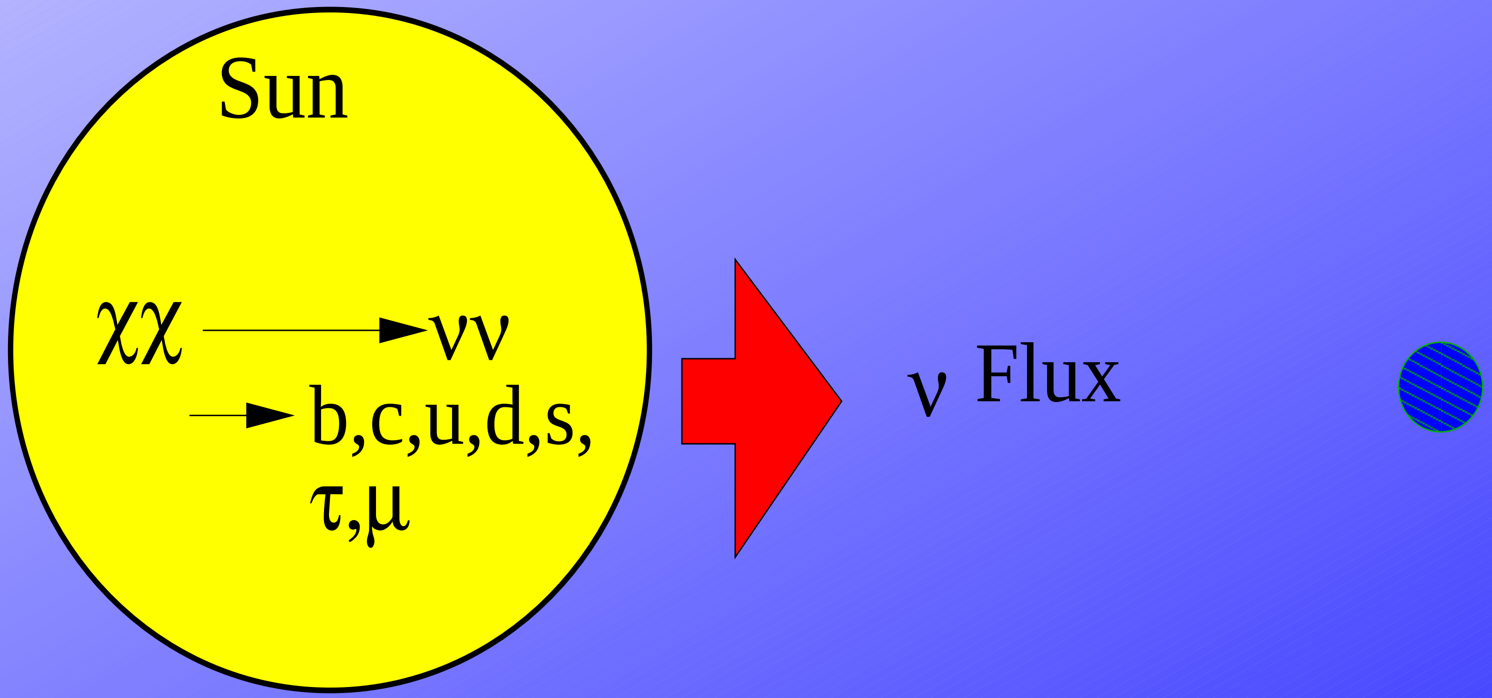


[Alner et al., PLB 616]

- Indirect detection observing the annihilation products (gamma rays, anti-matter, neutrinos).

When a WIMP goes through a celestial body, they can remain gravitationally trapped and a high density of WIMPs builds up.

Neutrinos are produced directly in the annihilation ($\chi\chi \longrightarrow \nu\nu$) but also in the subsequent decay of other SM particles (quarks, leptons, bosons).



The analysis of the neutrino signal in present and future detectors requires:

- neutrino flux on Earth:
    1. capture and annihilation rate
    2. neutrino production from annihilation
    3. propagation of neutrinos from production to detection
- detection of DM neutrinos at future LBL detectors
- extract information on WIMP properties (Br in channels, mass...)

1. WIMP capture and annihilation rate

WIMPs scatter off nuclei in the Sun and other celestial bodies. They have a non-negligible probability of being scattered off to a velocity smaller than the escape one. The WIMP gets trapped and an isothermal distribution forms.

$$\boxed{C_\odot \simeq 9 \times 10^{24}\mathrm{s}^{-1} \, \left(\frac{\rho_{local}}{0.3\mathrm{GeV}/\mathrm{cm}^3}\right) \left(\frac{\sigma}{10^{-2}\mathrm{pb}}\right) \left(\frac{50\mathrm{GeV}}{m_{DM}}\right)^2}$$

[Press and Spergel; Gould]

Two WIMPs can then annihilate each other into SM particles. In the Sun, equilibrium can be reached:

$$\boxed{\Gamma_{\mathrm{ann}} = \tfrac{1}{2} C_\odot}$$

2. Neutrino production from annihilations

From WIMP annihilations, a neutrino flux arises:

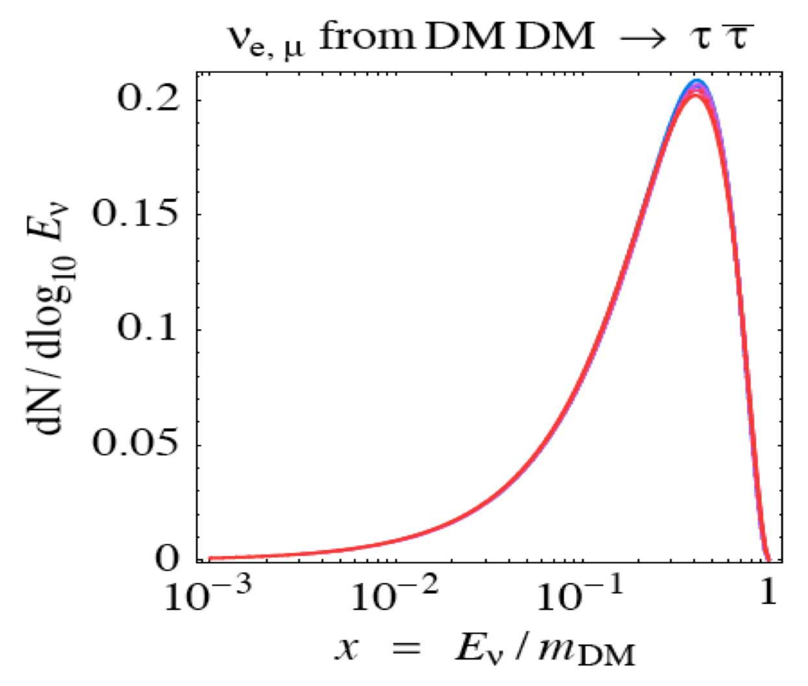
- directly: $\chi\chi \longrightarrow \nu\bar{\nu}$
- indirectly: $\chi\chi \longrightarrow$ SM particles $\longrightarrow \nu X$

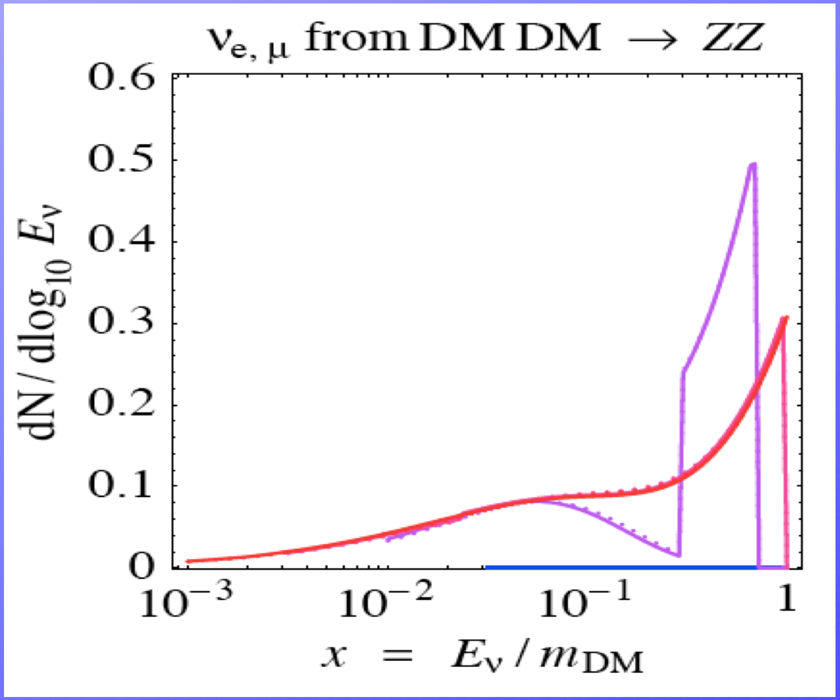
The neutrino flux is given by:

$$\boxed{\frac{d\phi}{dE} = \frac{\Gamma_{\mathrm{ann}}}{4\pi R^2} \sum_F \mathrm{Br}_F \frac{dN_F}{dE}}$$

The neutrino spectrum depends on the Br into the allowed channels.

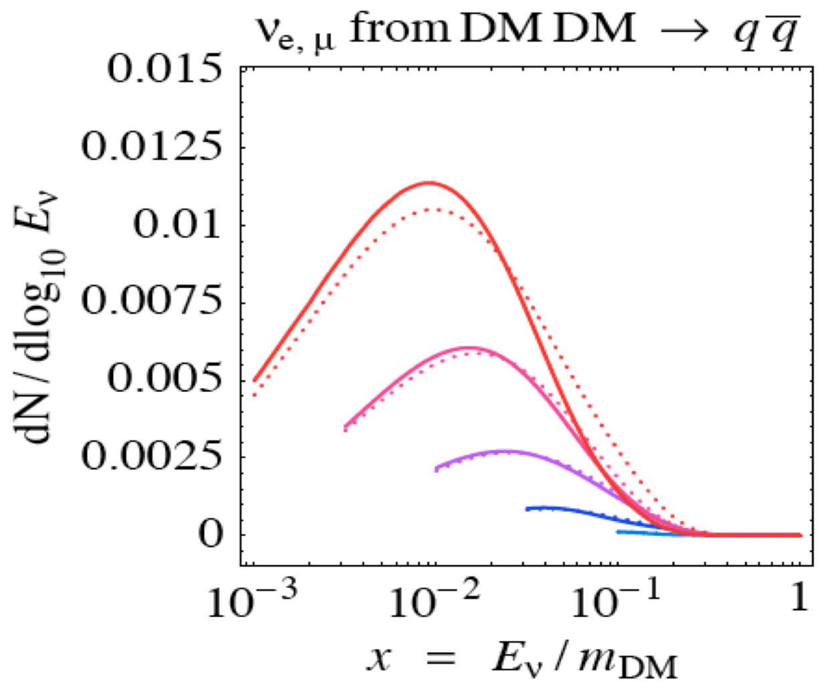
- direct neutrinos with $E_\nu = m_{\rm DM}$.
- taus produce a spectrum peaked at $E_\nu = 0.5 m_{\rm DM}$
- W, Z give a very hard spectrum

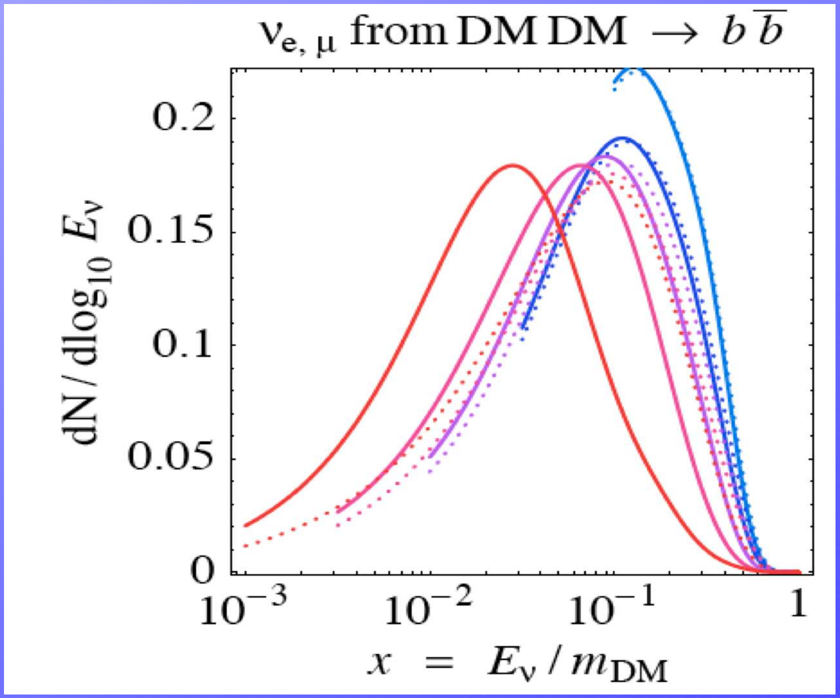




[Cirelli et al., NP B727]

- u, d, s quarks and muons are relatively long lived and loose most of their kinetic energy before decaying. Low energy neutrinos.
- b and c quarks loose energy due to interactions with the dense medium. Soft spectrum.





[Cirelli et al., NP B727]

The ν spectrum depends on the DM candidate considered.

- LSP in SUSY models: typically the branching ratio is $\propto m_f$. The BR into neutrinos is negligible. Dominant decay modes for light LSP: $b\bar{b}$ and $\tau\bar{\tau}$.
- Kaluza-Klein modes in extra-D models: BR$_{\nu\nu}$ can be as high as few %. Spectrum typically dominated by the $\tau\bar{\tau}$ channel.

Determining BR together with other properties (mass, elastic cross section...) will play an important role in establishing the nature of WIMPs.

3. Neutrino propagation

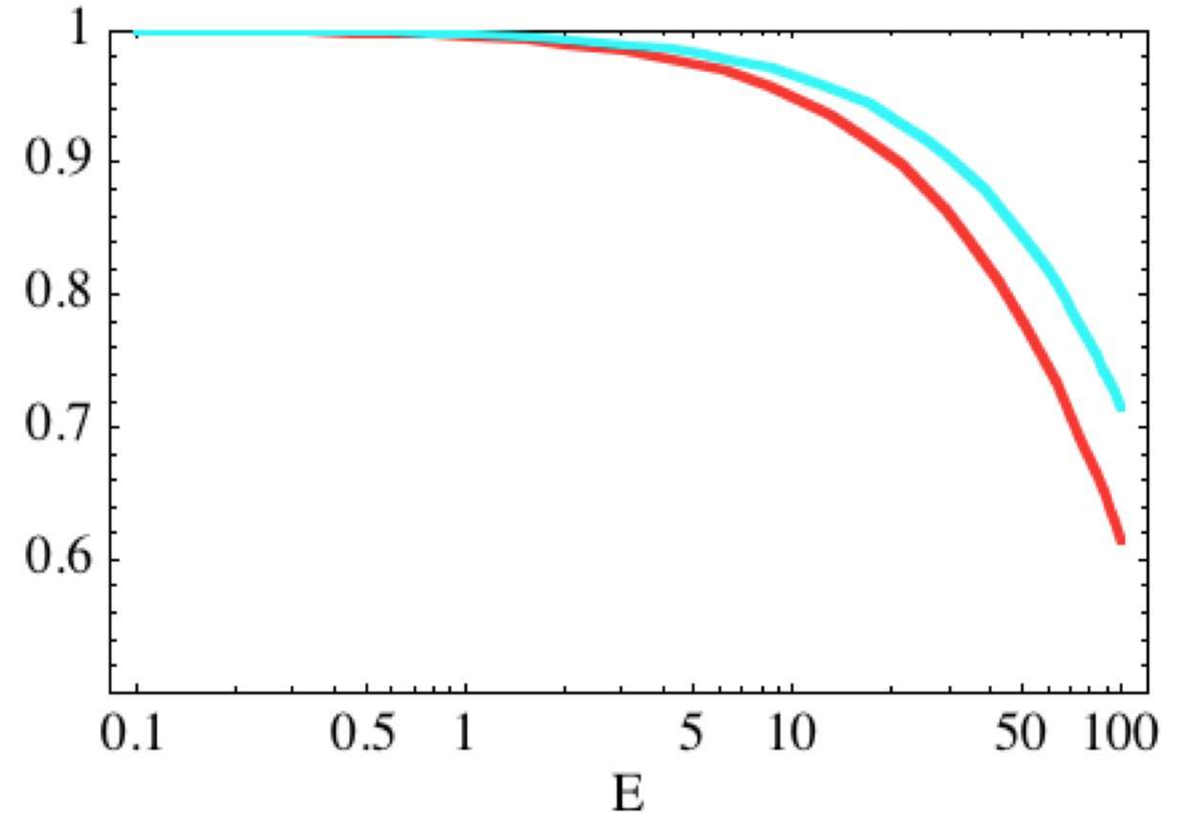
Once the neutrinos are produced, they travel from the interior of the Sun to the detector. Oscillation, energy loss and absorption effects need to be included.

- oscillations in vacuum and in matter (MSW effect)
- energy loss via NC interactions:

$$E_f = \frac{E}{1 + E\tau_i}$$

with $\tau_\nu = 1.01 \times 10^{-3}\ \mathrm{GeV}^{-1}$, $\tau_{\bar{\nu}} = 3.8 \times 10^{-4}\ \mathrm{GeV}^{-1}$

- absorption due to CC interactions: $P_f = (1 + E\tau_i)^{-\alpha_i}$ with $\alpha_\nu = 5.1$ and $\alpha_{\bar{\nu}} = 9.0$



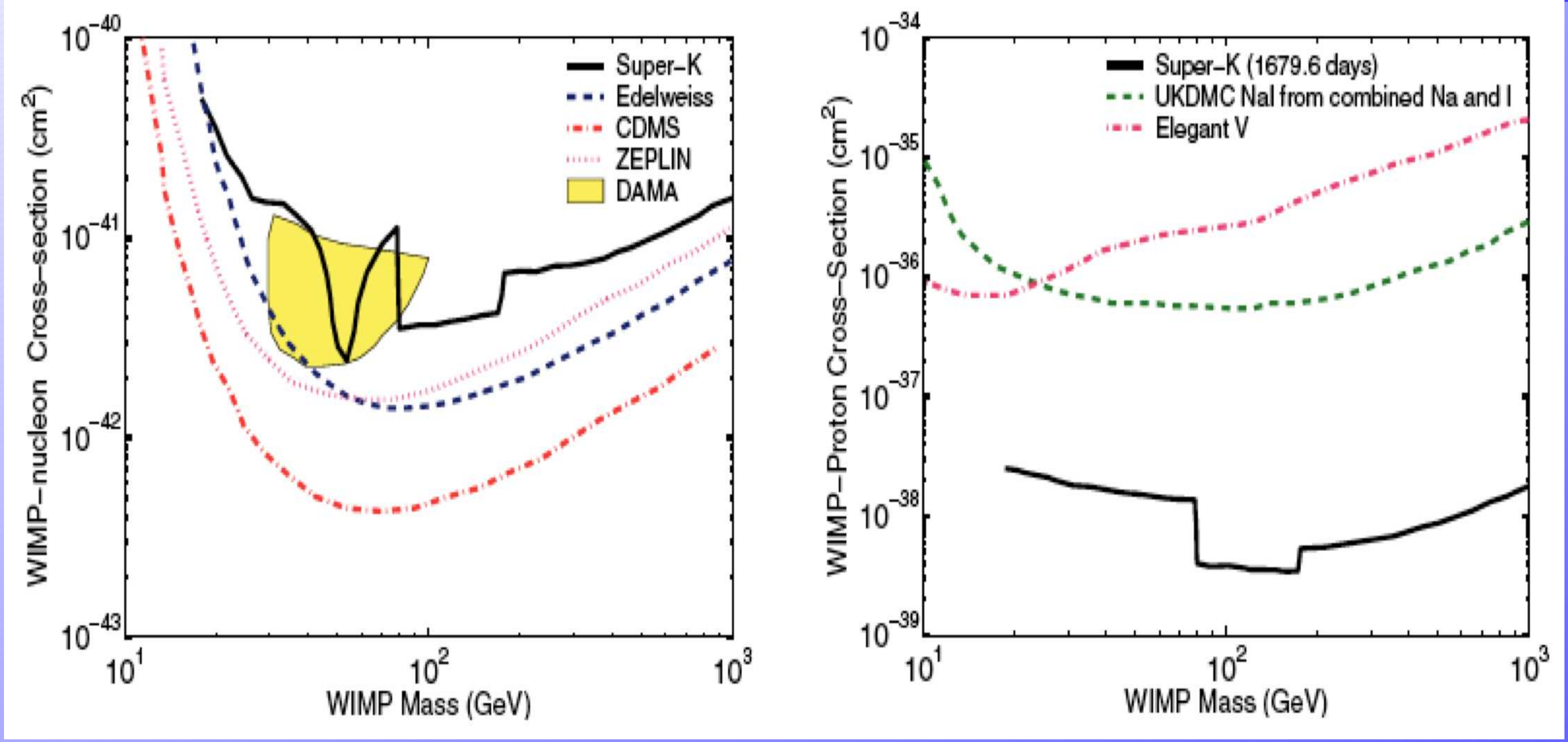
The τ produced by ν_τ CC interactions reinjects secondary energetic neutrinos.

4 – Detection of WIMP neutrinos

The DM neutrinos produced can be observed with neutrino detectors and neutrino telescopes.

● Super-Kamiokande (IMB, Kamiokande, MACRO) looked at through-going muons produced in the rock and put a strong bound on the flux of these neutrinos. Very limited information is obtained on the neutrino energy as these events are not contained.

● Neutrino telescopes (IceCube, ANTARES...) have a very large size and therefore can be used to detect these neutrinos at high energies.



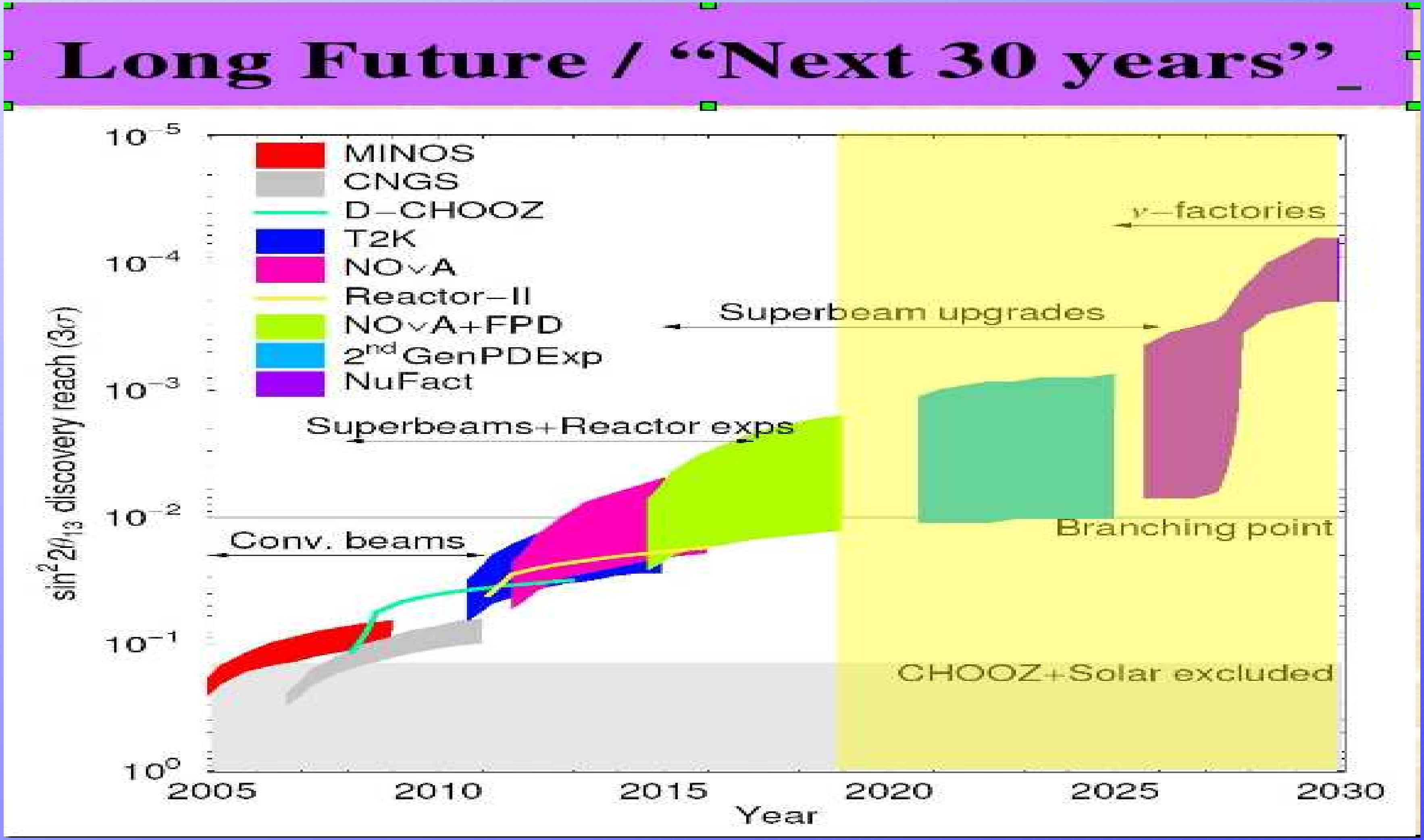
[Desai et al., PRD 70]

These experiments can only count the rates. $\boxed{BR\text{-}\sigma \text{ degeneracy}}$: the same rate can be obtained by trading off the annihilation channel with the cross section, i.e. a softer spectrum leads to less events due to the $\sigma_{\nu\text{detection}}$ dependence on energy but this can be compensated by a larger σ.

In the coming future, LBL neutrino oscillation experiments will search for θ_{13}, the type of neutrino mass hierarchy and CP-violation. They require very intense neutrino beams and very large detectors.

1. **Superbeams**: ν_μ flux from π decays. The next generation experiments are T2K (300 km) and NOνA (800 km). Possible future upgrades.
2. **Neutrino factories**: ν_μ and ν_e beam from μ decays. The spectrum is very well known. The detector needs to be magnetised.
   High energy neutrino factory: 25 GeV muons and $L \sim 3000$–7000 km.
   Low energy nufact: 4 GeV and $L \sim 1300$ km.
3. **Beta-beams**: ν_e beam from β-decay of high γ ions (^{6}He, ^{18}Ne, ^{8}Li, ^{8}B) .
   Typical energies from 200 MeV (low γ) to 2 GeV (high γ options).

4 – Detection of WIMP neutrinos



Long Future / “Next 30 years”_

The detectors under consideration at present are

- Water Cherenkov (SK and HyperK, MEMPHYS, UNO): they perform well below 1 GeV. They have poor energy resolution at $E > 10$ GeV. Not suitable for our purposes.

- Iron magnetised calorimeters (MINOS, MIND, INO): muons of tens of GeV can be contained in a sufficiently large detector. With the additional reconstruction of the hadronic energy, an energy resolution of $\sim 10\%$ can be achieved for muons with tens of GeV energy. [A. Cervera, private communication]

- Liquid Argon TPC (GLACIER, Flare): the tracks of leptons can be reconstructed as well as the hadronic part of the signal. The initial neutrino energy well measured.

- Totally active scintillator detectors: they could achieve good energy resolution for ν_e in the tens of GeV energy range.

The future detectors for LBL experiments have two important characteristics:

- large size
- good energy and angular resolution

Therefore, they can provide information for indirect WIMP searches.

Not only they can count the number of DM neutrinos, but more importantly

they can give information on the DM neutrino spectrum

and therefore on the DM properties (mass, Br, nature).

We perform an analysis for a specific detector: MIND (50 kton iron magnetised detector).

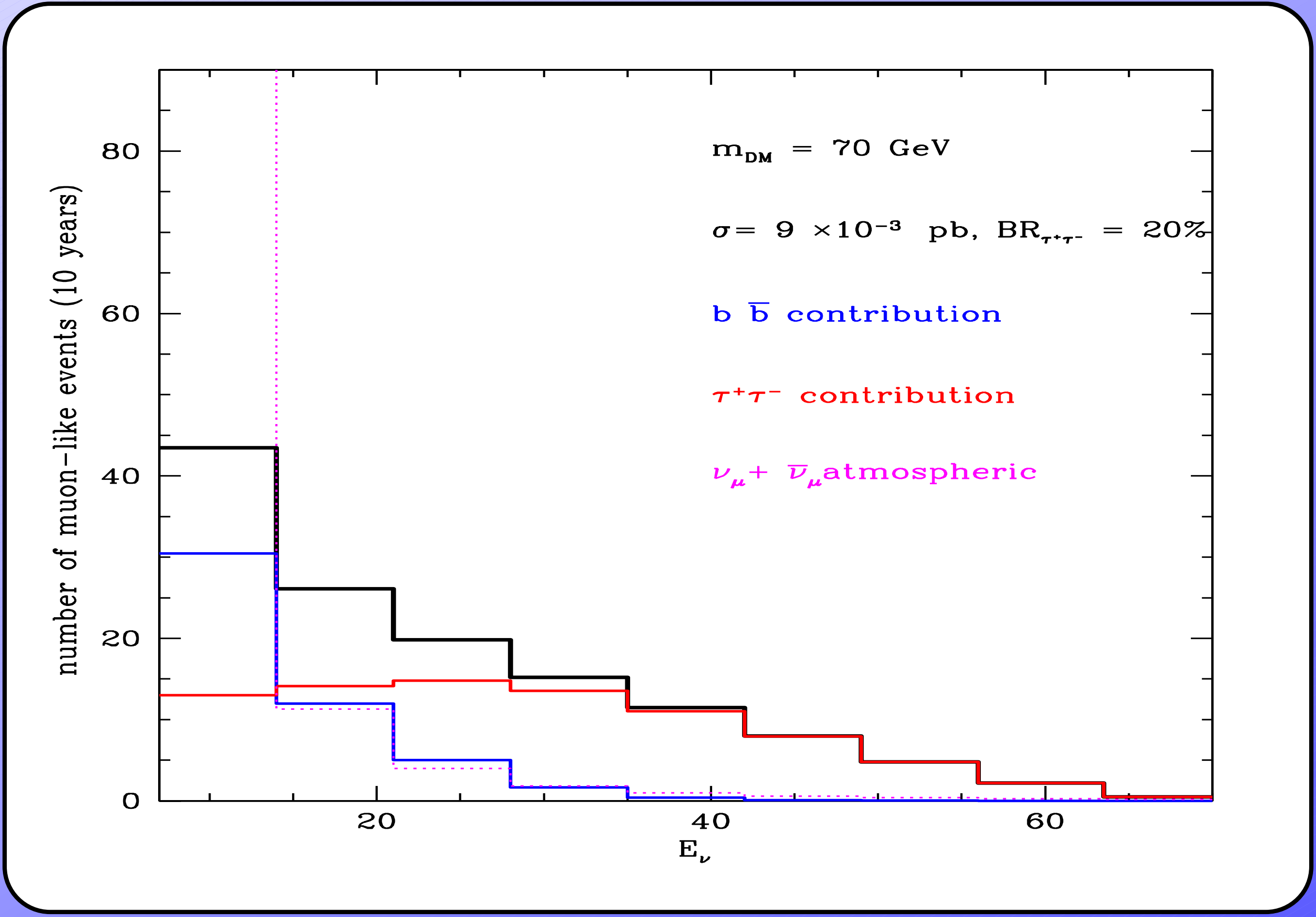
We exploit the angular and energy resolution:

- 5 GeV (7 GeV) binning in neutrino energy with 5 GeV threshold
- in order to reduce the atmospheric neutrino background, we use the angular resolution:

$$\theta_{rms} \sim \sqrt{\frac{\mathrm{GeV}}{E_\nu}}.$$

We evaluate the performance in reconstructing the neutrino spectrum [O. Mena, S. Palomares-Ruiz, SP, PLB664].

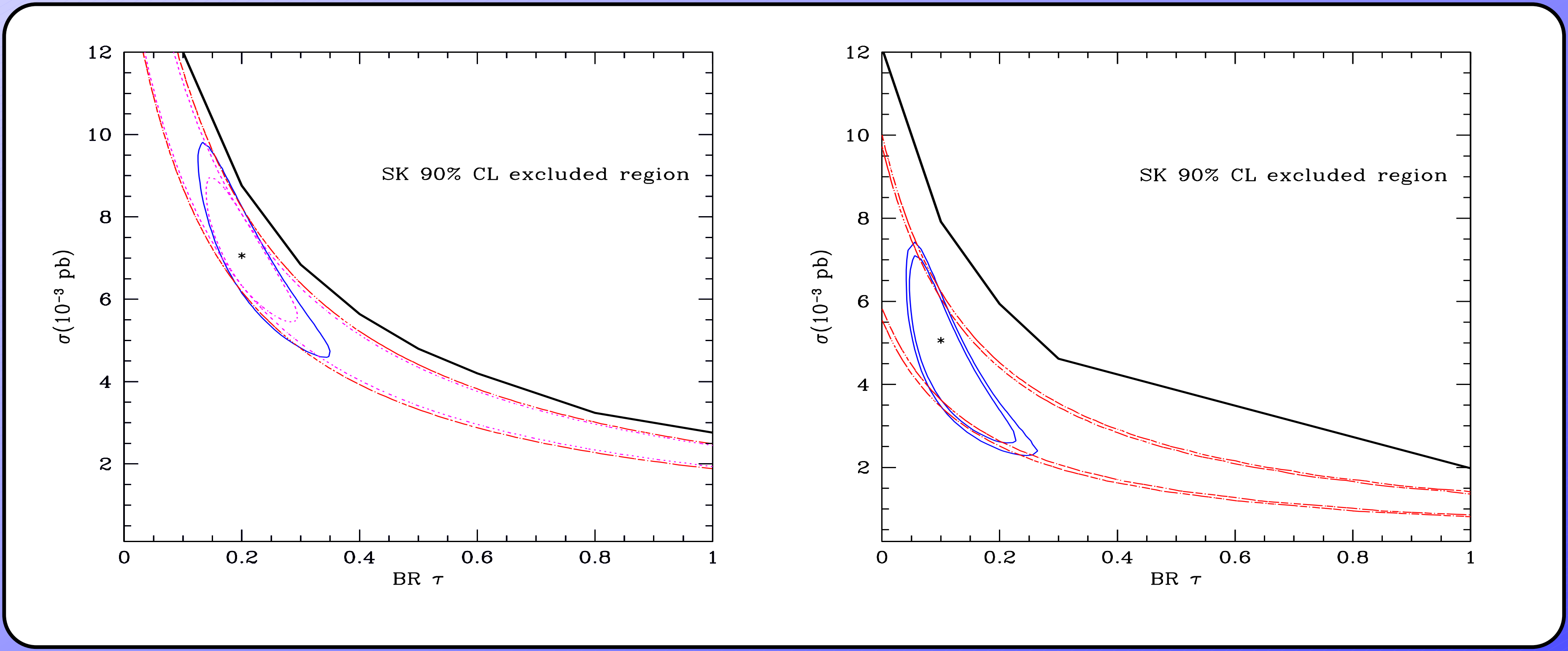
We study the number of neutrino events ($m_{DM} = 70$ GeV):



The shape of the spectrum gives information on the BR of annihilation.

The endpoint would allow to determine the WIMP mass or to pose a lower limit on its value.

Reconstruction of the WIMP annihilation BR:



[O. Mena, S. Palomares-Ruiz, SP, PLB664]

Indirect DM searches look for neutrinos from WIMP annihilation. WC detectors can only determine the total neutrino flux. MIND, TASD, LiAr detectors can reconstruct the spectrum of DM neutrinos from the Sun.

Future LBL neutrino detectors could constrain the BR of the SM annihilation channels.

They would play a crucial role in reconstructing WIMP properties,

in synergy with collider experiments and direct DM searches.

5 – MeV Dark Matter

MeV scalars have been proposed as DM candidates.

[Boehm and Fayet, NPB683]

- They constitute cold DM: structure formation compatible with observations
- They have been invoked to explain the 511 keV line [Boehm et al., PRL92]
- They provide an interesting link with neutrinos [Boehm et al., PRD77]

We introduce a model for ϕ annihilation. Large couplings are allowed only to neutrinos: SLIM (Scalar as LIght as MeV) [Boehm et al., PRD77].

$$\boxed{g \phi \nu N}$$

The cross section for annihilation is:

$$\boxed{\sigma v \sim \frac{g^4}{4\pi} \frac{m_N^2}{(m_\phi^2 + m_N^2)^2}}$$

- A mass for neutrinos arises:

$$\boxed{m_\nu \simeq \frac{g^2}{16\pi^2} m_N \left(\log \frac{\Lambda^2}{m_N^2} - \frac{m_\phi^2}{m_N^2 - m_\phi^2} \log \frac{m_N^2}{m_\phi^2} \right)}$$

It is possible to relate neutrino masses with the DM annihilation cross section:

$$\boxed{m_\nu \simeq \sqrt{\frac{<\sigma v>}{128\pi^3}}\, m_N^2 \left(1 + \frac{m_\phi^2}{m_N^2} \log \frac{\Lambda^2}{m_N^2} \right)}$$

For $< \sigma v >= 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$, we get eV-subeV neutrino masses!

Indication in favour of a low energy new physics (at or below the electroweak scale)? A theory needs to be developed (work in progress).

Constraints on SLIMs

- Big Bang Nucleosynthesis: for masses > 10 MeV no effect, for $m_\phi \sim 1$–10 MeV increase of T_ν.

- core-collapse SN: no change of neutrino-sphere if the nucleon-SLIM cross section is small. The neutrino diffusion scale $\lambda \sim (\sigma n_\phi)^{-1} \sim 30$ cm (similar to the standard case).

- meson decays: from distorsion of the electron and muon spectrum one obtains $g < 10^{-2}$. With the improvement of the experimental sensitivity, possible signal in the future.

- positron emission from galactic center (511 keV line): requires an interaction of SLIMs with electrons mediated by a heavy charged particle.

6 – Can we test MeV DM?

Indirect detection of neutrinos from DM annihilations in the galaxy [S. Palomares-Ruiz, SP, PRD77].

The flux of neutrinos:

$$\boxed{\frac{d\Phi}{dE}(\psi, E) \propto \langle \sigma v \rangle \frac{dN}{dE} \frac{1}{m_{\rm DM}^2} \int_{\text{line of sight}} ds \rho^2(r(\phi, s))}$$

In order to maximise the number of events and due to the poor information on the neutrino direction, we consider the flux from all directions. This reduces the impact of the shape of the DM profile in the inner part of the galaxy.

We introduce:

$$J_{\rm avg} = \frac{1}{2R_{\rm sc}\rho_0^2} \int_{-1}^{1} \int_{0}^{l_{\rm max}} \rho^2(r) dl d(\cos\psi)$$

Depending on the profile, $J_{\rm avg}$ can vary of a factor ~ 60.

For annihilations $\phi\phi \to \nu\nu$, we have $E_\nu = m_\phi$ and the flux of electron antineutrinos is:

$$\boxed{\frac{d\Phi_e}{dE}(\psi, E) \propto \langle\sigma v\rangle J_{\rm avg}\frac{1}{m_\phi^2}\frac{1}{3}\delta(E_\nu - m_\phi)}$$

Very clear signature: **a sharp peak in the neutrino spectrum**.

The number of neutrino events is:

$$\boxed{\mathcal{N} = \sigma_{\rm det}(m_\chi)\, \Phi\, n_{\rm target} t\epsilon}$$

- $\langle\sigma v\rangle$ is constrained to be $3 \times 10^{-26}\ {\rm cm}^3/{\rm s}$ by requiring $\Omega_\phi h^2 = 0.12$.
- an uncertainty of a factor ~ 50–100 is introduced by $J_{\rm avg}$

The dominant interaction is the inverse beta decay

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

- few events per Megaton year ⇒ large detectors
- large backgrounds ⇒ very good energy resolution at MeV
- low threshold to be sensitive to MeV neutrinos

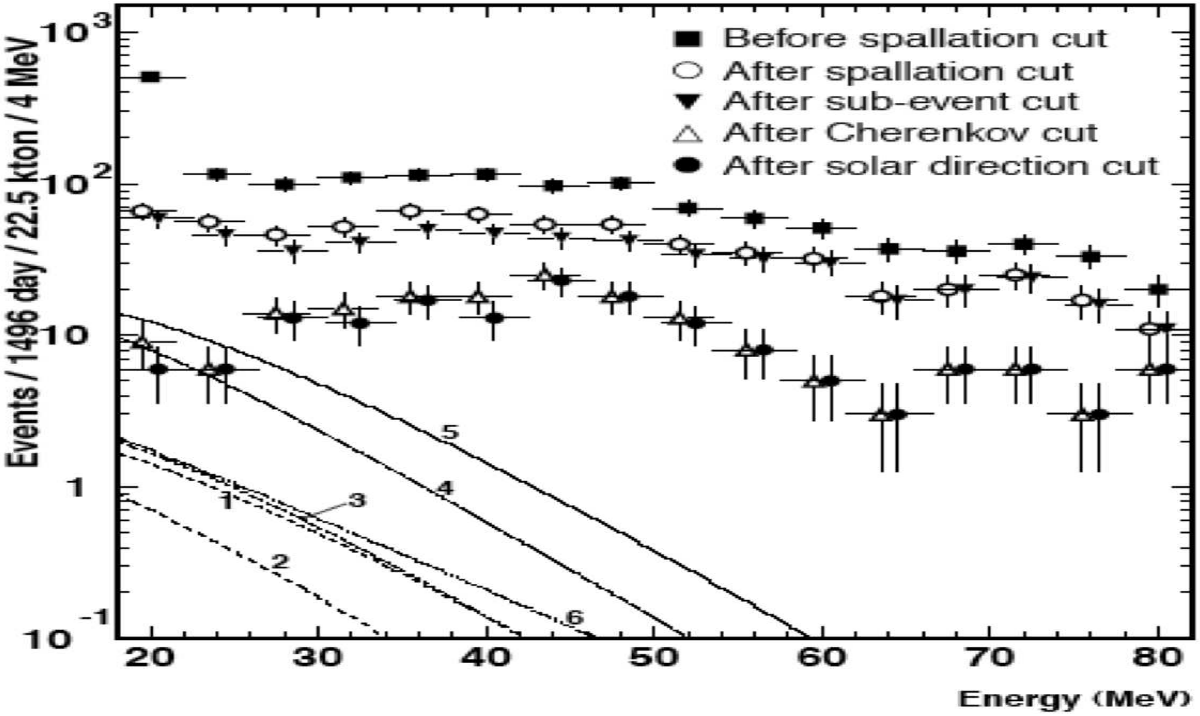
The detectors which have these characteristics are Super-Kamiokande and LENA.

The main backgrounds depend on the type of detector (WC or scintillator):

- solar neutrino flux: relevant for WC detectors below 10 MeV.
- reactor $\bar{\nu}_e$: dominant flux below 10 MeV.
- atmospheric electron neutrinos: becomes important at high energies.
- invisible muons from ν_μ and $\bar{\nu}_\mu$ interactions: important for WC detectors.
- diffuse supernova neutrino background

Bounds from Super-Kamiokande

The Super-Kamiokande detector has sensitivity in the relevant energy window. Searches of DSNB neutrinos in the 18 MeV–82 MeV.



[Malek et al., (SK Collaboration), PRL90 2003]

The signal in the energy interval $[E_l, E_{l+1}]$:

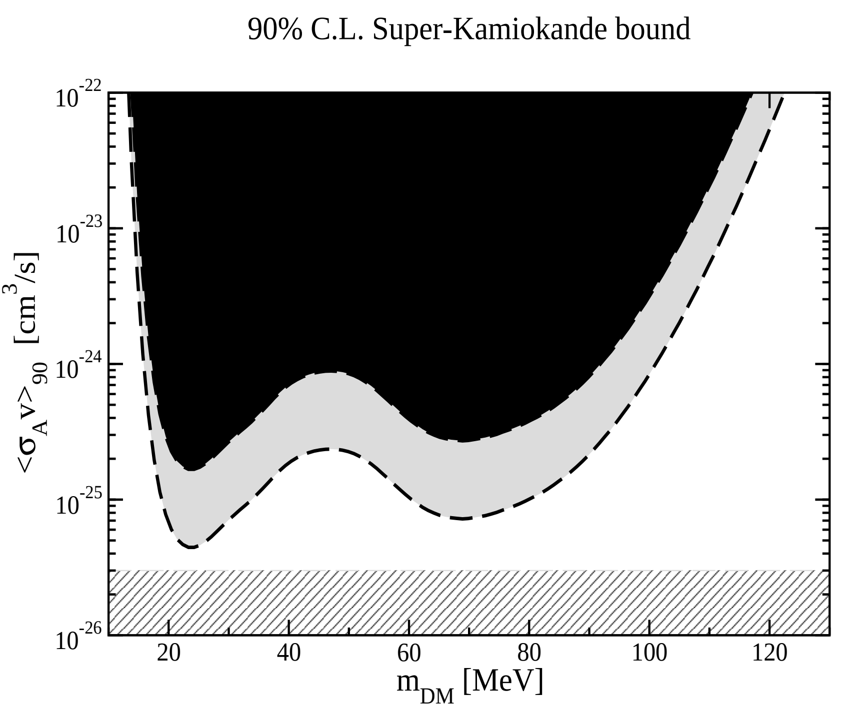
$$\boxed{N_l \propto \int \left(\frac{d\sigma_{\rm f}^{\bar{\nu}}}{dE_e}(m_\chi, E_e) + 1/2 \frac{d\sigma_{\rm b}^{\nu,\bar{\nu}}}{dE_e}(m_\chi, E_e) \right) dE_e}$$

The main backgrounds are due to atmospheric $\bar{\nu}_e$ and Michel electrons from invisible muons. The background can be reduced using energy resolution: $\sigma = 0.40\sqrt{E/\mathrm{MeV}}\ \mathrm{MeV} + 0.03E$.

6 – Can we test MeV DM?

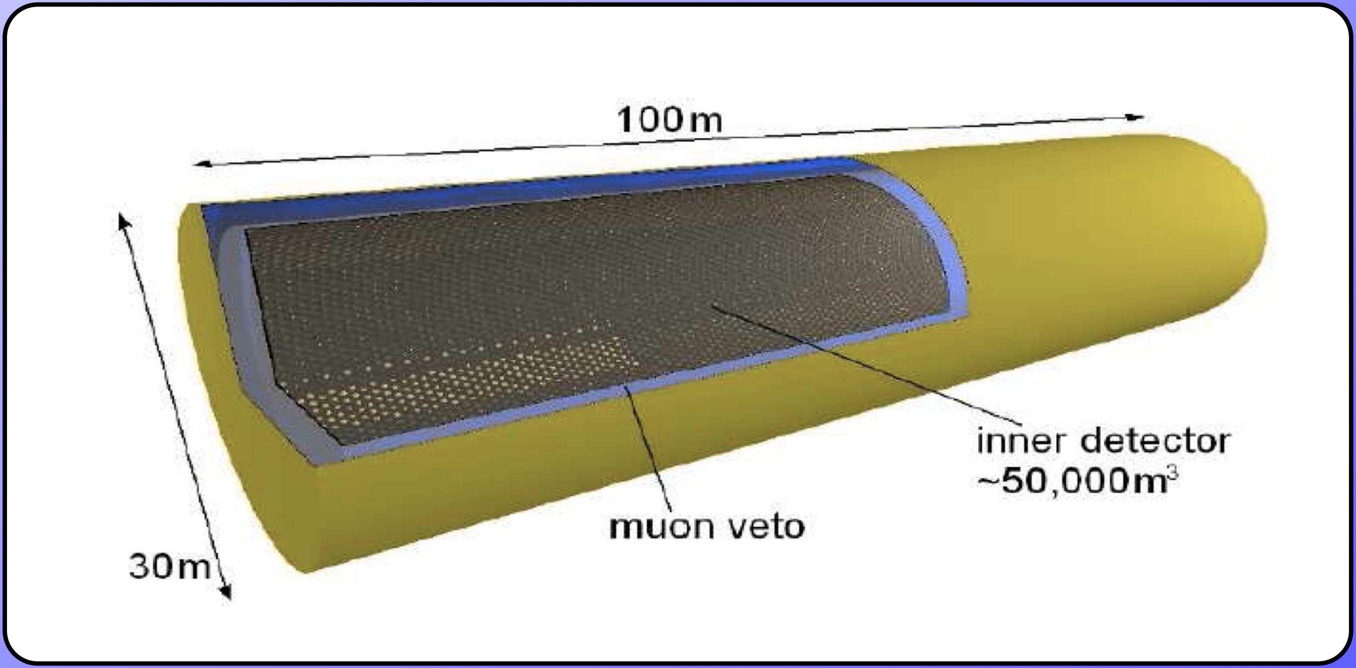
The 90%CL bound on $\langle \sigma v \rangle$ is

$$\langle \sigma v \rangle_{90} = \alpha_{90} \, \frac{6\, m_\phi^2\, N_s}{t N_{\rm target} J_{\rm avg}}$$



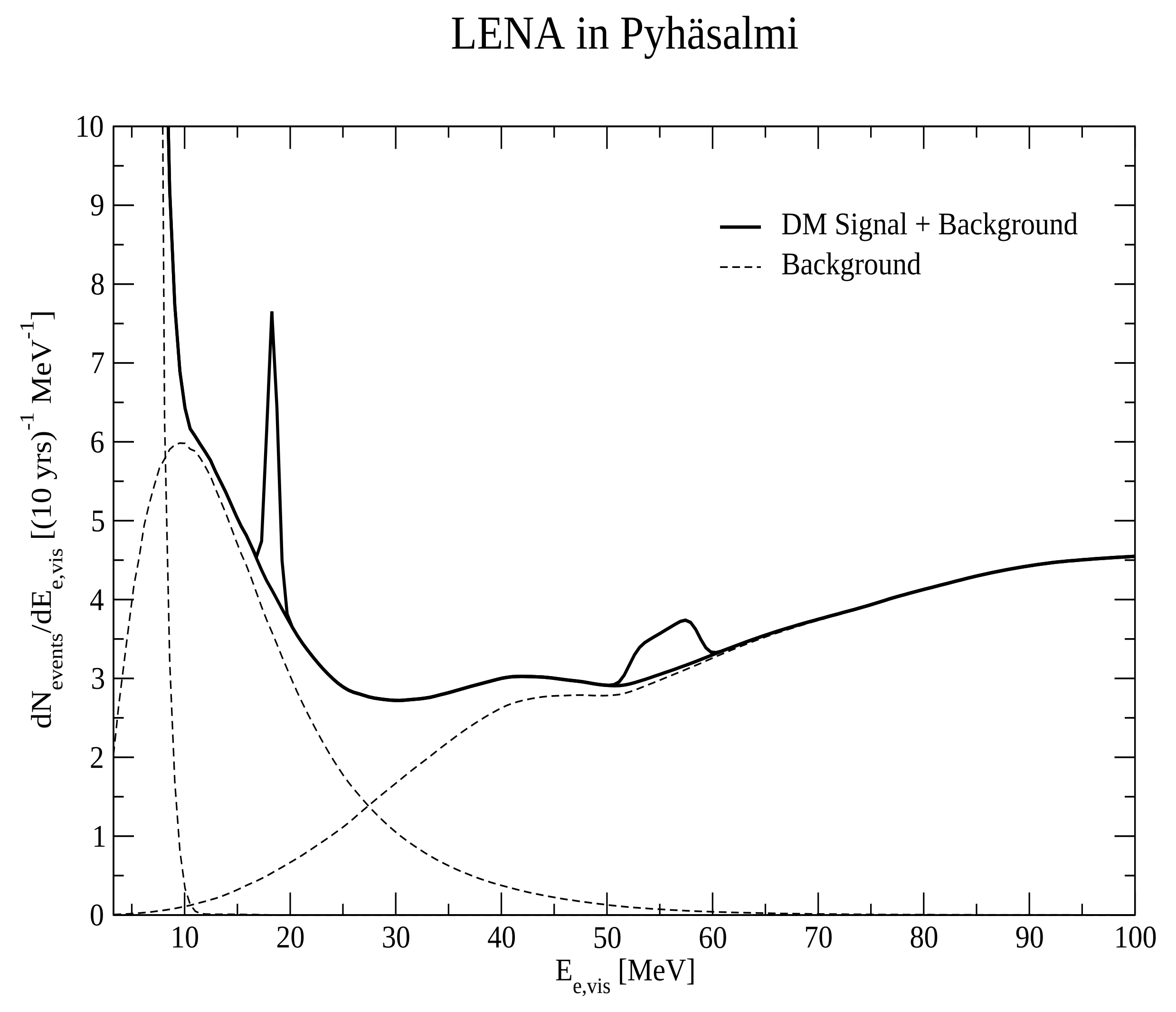
Future perspectives: LENA

LENA is a $50 \times 10^3 \mathrm{m}^3$ scintillator detector proposed for the future.



It will have excellent energy resolution: $\sigma = 0.10\sqrt{E/\mathrm{MeV}}\mathrm{MeV}$ and allow for a very sensitive search of this signature.

The expected signal at LENA for $m_\phi = 20\ \mathrm{MeV}$–$60$ MeV:



7 – Conclusions

- Establishing the nature and properties of Dark Matter is of crucial importance.
- For WIMP DM, the neutrino flux depends on the DM couplings. Future LBL experiments might have the sensitivity to constrain DM masses and Br.
- For MeV DM, SK and LENA can constrain the DM annihilation cross section and possibly provide a positive signature.

DM neutrinos can provide crucial information on DM,

in combination with results from collider and particle experiments

as well as from direct and indirect detection.