Downward-going tau neutrinos and Dark Matter

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based on *N. Fornengo, V. Niro, arXiv:1108.2630*

Outline

Indirect Dark Matter detection

The Dark Matter (DM): 23% of the matter present in the Universe

Indirect detection: look for the products of DM self-annihilation or decay occurring in GH, in EG environment, in celestial bodies, like the Sun and the Earth

Typical way of looking for a neutrino signal: an excess of upward-going muons $\Rightarrow$

- large conversion area offered by the rock below the detector
- well-established and efficient experimental techniques
- ν_μ atmospheric neutrinos are the main source of background

Our proposal: downward-going tau events $\Rightarrow$

- DM annihilation typically produces similar amount of all neutrino flavors
- atmospheric neutrinos ν_τ component is very suppressed
- oscillations is basically inoperative in the downward-going direction for the atmospheric background
- it might be a competitive discovery channel

Dark Matter

The differential neutrino flux from the Sun is:

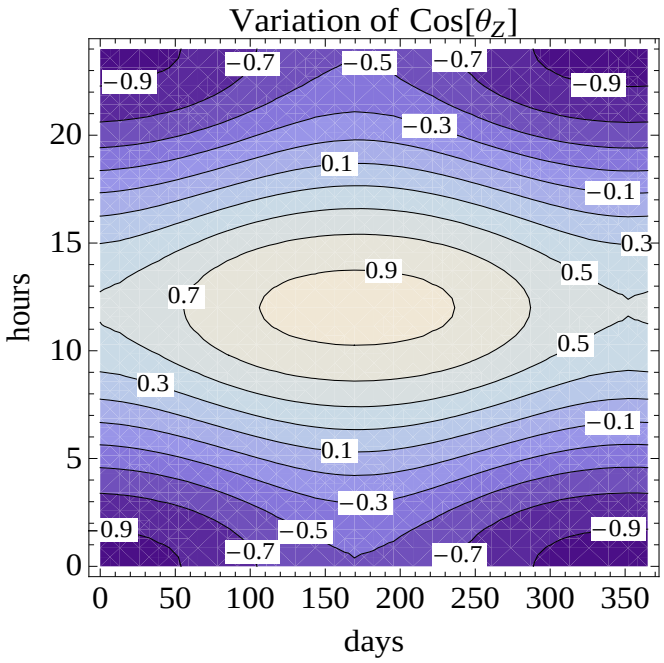
$$\frac{d\phi_\nu}{dE_\nu} = \sum_f BR_f \frac{\Gamma_\odot}{4\pi d^2} \frac{dN_\nu^f}{dE_\nu}$$

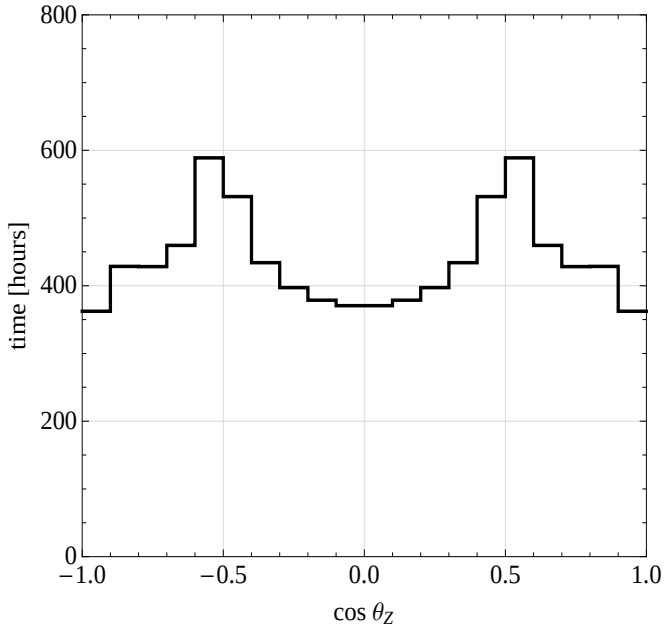
Propagation: oscillation, neutral and charged current interactions

Our examples: i) annihilation into neutrinos with $BR_{\nu_e\bar{\nu}_e} = BR_{\nu_\mu\bar{\nu}_\mu} = BR_{\nu_\tau\bar{\nu}_\tau} = 1/3$

ii) annihilation into tau leptons with $BR_{\tau\bar{\tau}} = 1$

Apparent motion of the Sun for a detector at latitude $\varphi = 36^\circ$

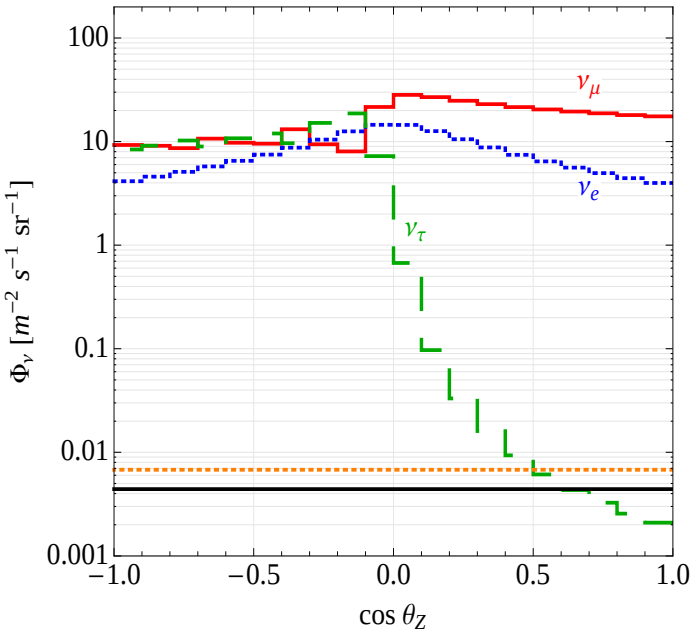




Backgrounds

Sources of background for the ν_τ signal from DM annihilation:

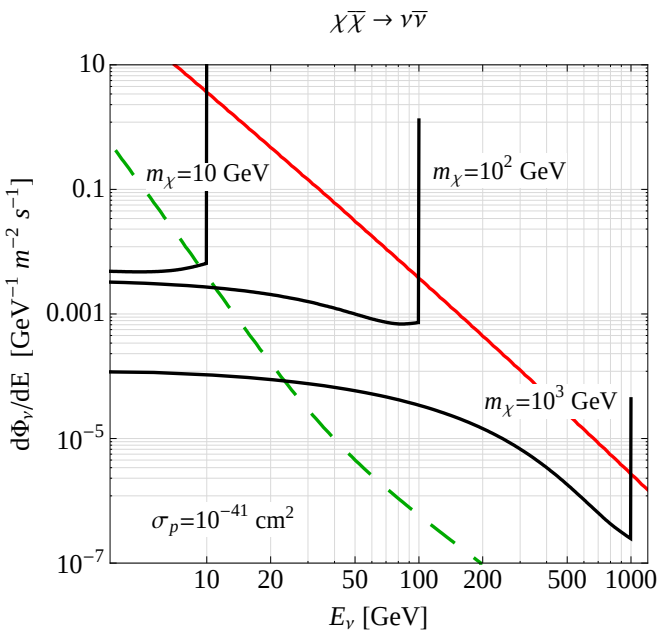
- ν_τ atmospheric background coming from oscillation of atmospheric ν_μ
- very small intrinsic ν_τ contribution coming from decay of charmed particles
- ν_e and ν_μ neutrinos produced in the solar corona by cosmic-ray collisions
  $\rightarrow$ they generate ν_τ during their propagation to the Earth
- ν_μ produced in cosmic-ray interactions with the interstellar medium
  $\rightarrow$ they generate ν_τ from the Galactic plane

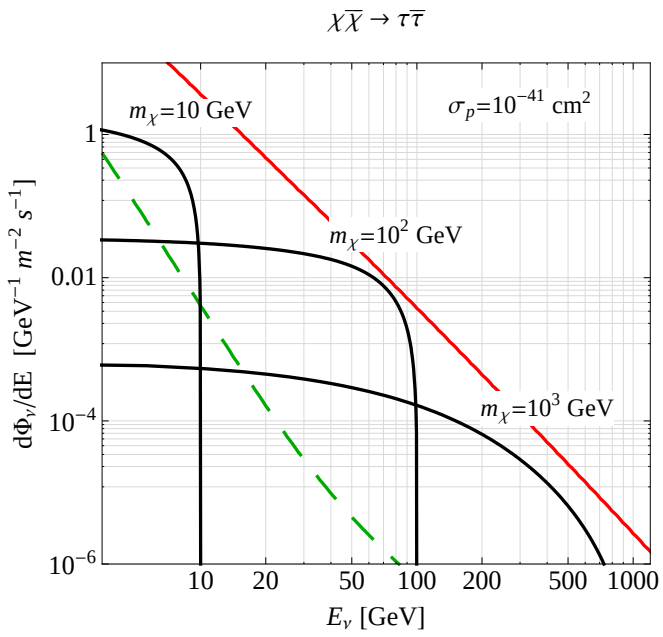


The atmospheric ν_τ background is sizebly reduced for $\cos\theta_Z \geq 0$ and is much smaller than the ν_e and ν_μ fluxes.

Black: solar corona neutrinos
Yellow: galactic contribution

Backgrounds





Black: total downward-going ν_τ fluxes integrated (zenith angles with $\cos\theta_Z \geq 0$)
Green: total downward-going ν_τ background fluxes
Red: total downward-going ν_μ background fluxes

$\Rightarrow$ the signal is dominant over the background in the down-going ν_τ channel, especially at high energies where the tau cross section is not suppressed by mass threshold.

Signals at water Cherenkov detectors

For GeV-TeV energy range: CC ν_τ interactions in water Cherenkov detectors lead to multiple Cherenkov rings $\rightarrow$ statistical methods to identify ν_τ and hadronic decays of tau leptons ($BR_\tau^h \simeq 64\%$) because of a more spherical topology than the backgrounds.

Backgrounds to ν_τ CC events with hadronic tau decay:

- NC events from ν_e and ν_μ atmospheric neutrinos
- CC events from ν_e and ν_μ atmospheric neutrinos

$\Rightarrow$ The SK Collaboration: number of event selection criteria to reduce these backgrounds; neural network and maximum likelihood techniques to discriminate tau neutrino events.

	Data	$\nu_{e,\mu}$ BKG MC	CC ν_τ MC
Generated in fiducial volume	–	17135(100%)	78.4 (100%)
$E_{vis} > 1.33$ GeV	2888	2943 (17.2%)	51.5 (65.7%)
Most energetic ring e-like	1803	1765 (10.3%)	47.1 (60.1%)
Likelihood > 0	649	647 (3.8%)	33.8 (43.1%)
NN output > 0.5	603	577 (3.4%)	30.6 (39.0%)

		SK-I	SK-II
CC $\nu_e + \overline{\nu}_e$	QE	2.3%	3.8%
	Single meson	8.2%	8.5%
	DIS	41.4%	40.0%
	total	51.9%	52.3%
CC $\nu_\mu + \overline{\nu}_\mu$	QE	<0.1%	<0.1%
	Single meson	0.6%	0.5%
	DIS	19.9%	20.0%
	total	20.6%	20.6%
NC		27.5%	27.1%

hep-ex/0607059, Tokufumi Kato's PhD thesis

Signals at water Cherenkov detectors

The atmospheric ν_e and ν_μ fluxes are usually larger than the DM fluxes
$\Rightarrow$ the misidentification has a relevant impact on the actual performance of water Cherenkov detectors in identifying ν_τ events.

Our analysis:

- $E_{\rm vis}^{\rm min} = 3.5$ GeV as lower limit on the visible energy
  $\rightarrow$ a specific detector should choose the minimal visible energy able to maximize the number of correctly identified tau events with respect to the misidentified ones
- total downward-going events ($\cos\theta_Z \geq 0$)
- favourable situation in which the track events from ν_μ CC interactions will always be detected
- as misidentified background events we will only considered NC events from ν_e and ν_μ atmospheric neutrinos and CC events from ν_e interactions

Signal events from hadronic tau decay

The total number of contained events for charged current ν_τ interactions is:

$$N_\tau^{\mathcal{CC}}\Big|_{\mathcal{S},\mathcal{B}} = M_{\rm det} N_y \times \int_{E_{\rm vis}^{\rm min}}^{E_{\rm vis}^{\rm max}} dE_{\rm vis} \int d\Omega \;\; \eta(\theta) \;\; \frac{d\mathcal{I}_\tau^{\mathcal{CC}}}{d\Omega\, dE_{\rm vis}}\Big|_{\mathcal{S},\mathcal{B}} ,$$

$M_{\rm det}$ is the detector mass, N_y the number of years of exposure and $\eta(\theta)$ is the on-source duty factor (we take $\eta(\theta)$ =1/2 for bkg).
The visible energy $E_{\rm vis}$ is the sum of the energy $E_{h,1}$ of the broken nucleon and the hadronic energy $E_{h,2}$ of the tau decay.

Hadronic tau decay

$$\frac{d\mathcal{I}_\tau^{\mathcal{CC}}}{d\Omega\, dE_{\rm vis}}\Big|_{\mathcal{S},\mathcal{B}} = \int_{E_{\rm vis}}^{\infty} dE_\nu \int_{E_\tau^{\rm min}}^{E_\nu} dE_\tau \; \frac{d\phi_{\nu_\tau}}{d\Omega dE_\nu}\Big|_{\mathcal{S},\mathcal{B}} \Sigma_\tau^{\mathcal{CC}}(E_\tau, E_\nu) \frac{1}{E_\tau} \frac{dn_\nu}{dz_\nu}$$

with $\Sigma_\tau^{\mathcal{CC}}(E_\tau, E_\nu) = N_A \left(\mathcal{Z} \frac{d\sigma^p_{\nu_\tau}}{dE_\tau}(E_\tau, E_\nu) + \mathcal{N} \frac{d\sigma^n_{\nu_\tau}}{dE_\tau}(E_\tau, E_\nu) \right)$,
$E_\tau^{\rm min} = \max[m_\tau, E_\nu - E_{\rm vis}]$ and $z_\nu = (E_\nu - E_{\rm vis})/E_\tau$.

Background events

ν_e and ν_μ neutral-current interactions

$$\left.\frac{d\mathcal{I}^{\mathcal{NC}}_{e,\mu}}{d\Omega\, dE_{\rm vis}}\right|_{\mathcal{B}} = \int_{E_{\rm vis}}^{\infty} dE_\nu \left.\frac{d\phi_{\nu_e,\nu_\mu}}{d\Omega dE_\nu}\right|_{\mathcal{B}} \Sigma^{\mathcal{NC}}_{e,\mu}(E_{\rm vis}, E_\nu)$$

The visible energy is given by $E_{\rm vis} = E_\nu - E'_\nu$, E_ν being the initial neutrino energy and E'_ν the final ones.

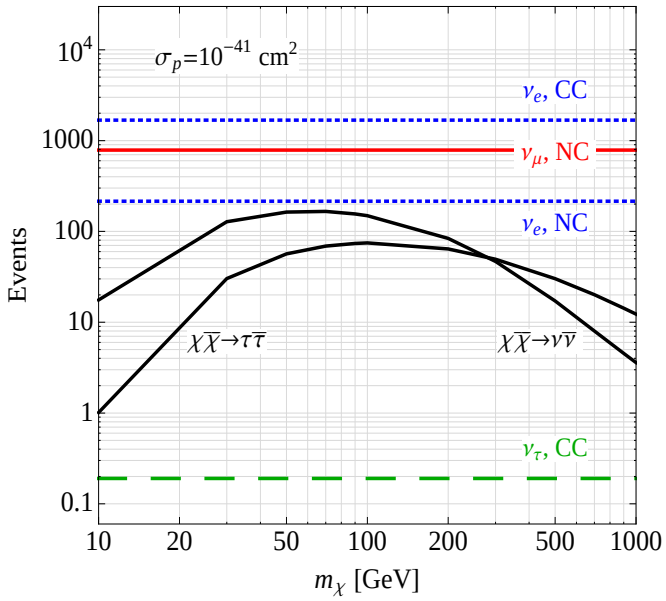
ν_e charged-current interactions

$$\left.\frac{d\mathcal{I}^{\mathcal{NC}}_{e,\mu}}{d\Omega\, dE_{\rm vis}}\right|_{\mathcal{B}} = \left.\frac{d\phi_{\nu_e}}{d\Omega dE_{\rm vis}}\right|_{\mathcal{B}} \Sigma^{\mathcal{CC}}_{e,\rm TOT}(E_{\rm vis})$$

The visible energy $E_{\rm vis}$ is equal to the full initial neutrino energy E_ν.

Contained hadronic events

Number of signal events expected for $M_{\rm det} N_y$ =1 Mton×year: from 1 to 100, depending on m_χ and BR_f. Higher signals in the range from 30 GeV up to 200-300 GeV.



lower limit on the visible energy: $E_{\rm vis}^{\rm min} = 3.5$ GeV,

zenith angles with $\cos\theta_Z \geq 0$,

hadronic tau from ν_τ background: small,

ν_e CC events: the biggest background.

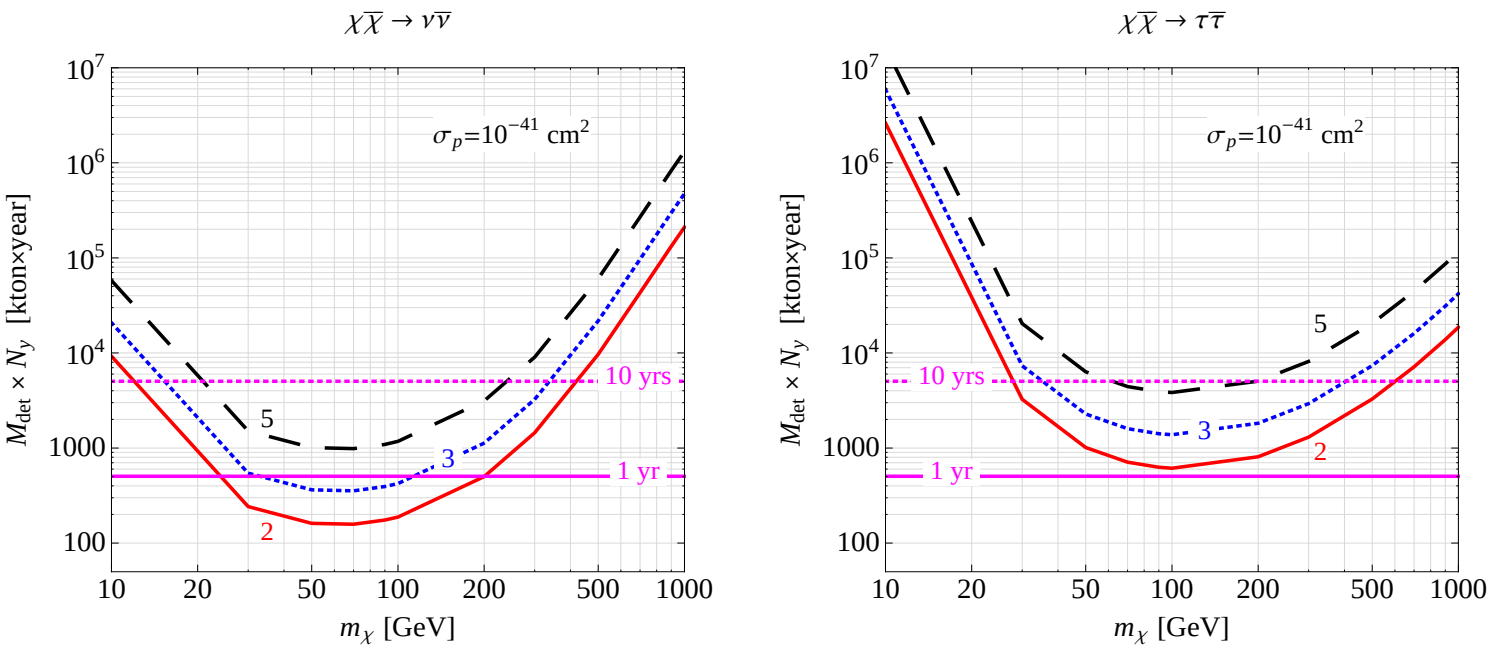
Neutral current + charged current events from atmospheric ν_e and ν_μ
$\Rightarrow$ problem if they are not controlled at a level better than a few percent.

Possible way to reduce the misidentification background could be obtained considering specific tau hadronic decays (multiple pion production) and finding suitable cuts to statistically distinguish these events from the CC/NC.

Statistical significance

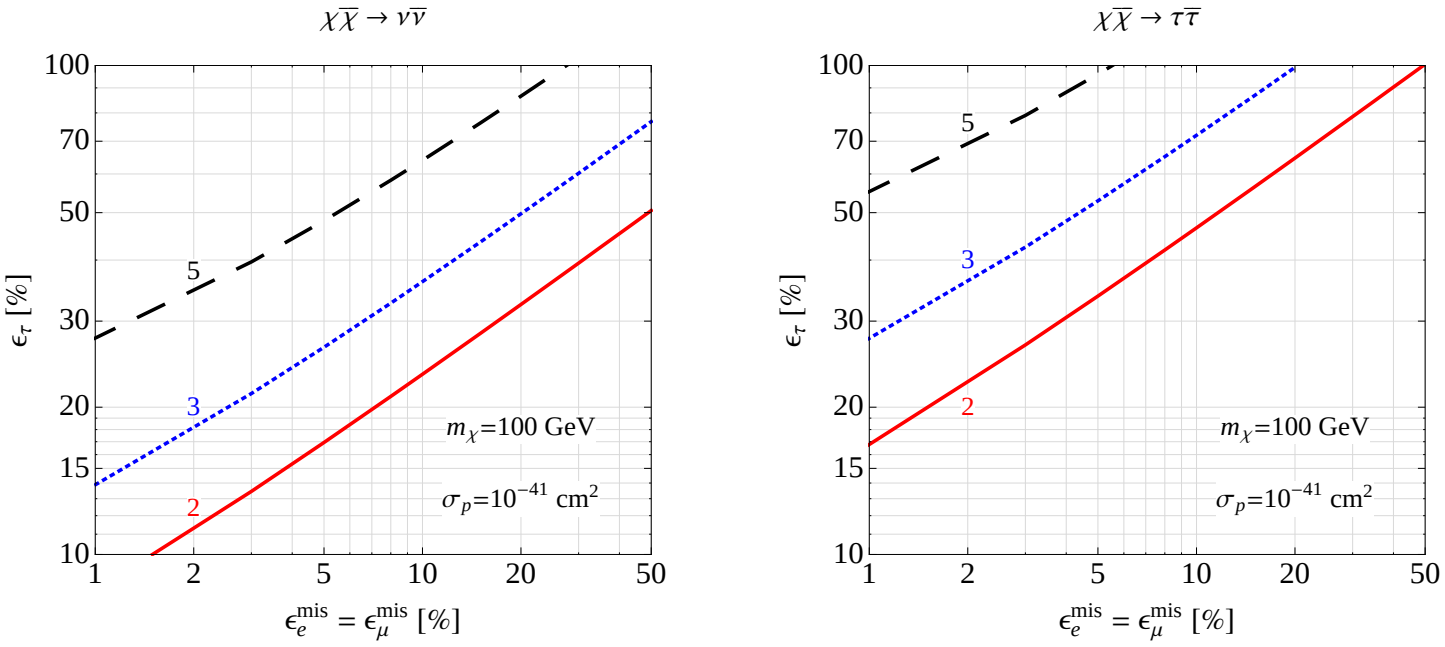
$$\varsigma \equiv \frac{S}{\sqrt{S+B}}\,,$$

with $B = \epsilon_\tau \; N_\tau^{\mathcal{CC}}\big|_{\mathcal{B}} + \epsilon_\mu^{\rm mis} \; N_\mu^{\mathcal{NC}}\big|_{\mathcal{B}} + \epsilon_e^{\rm mis} \left(N_e^{\mathcal{NC}}\big|_{\mathcal{B}} + N_e^{\mathcal{CC}}\big|_{\mathcal{B}} \right)$. We have fixed $\epsilon_\tau = 40\%$, $\epsilon_e^{\rm mis} = \epsilon_\mu^{\rm mis} = 4\%$.



10 yrs of data taking: 5 σ significance for m_χ between 20-300 GeV (60-200 GeV) for annihilation into $\nu\bar{\nu}$ ($\tau\bar{\tau}$).

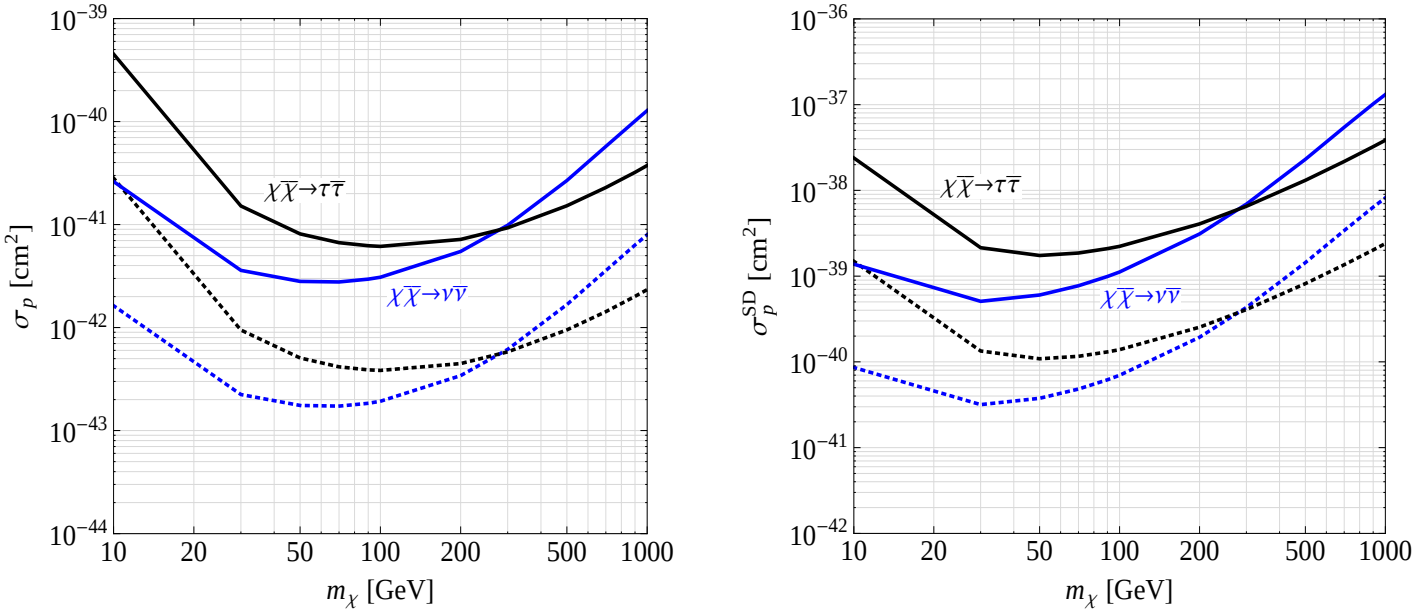
Misidentification parameters



Dependence of ς on $\epsilon_e^{\rm mis} = \epsilon_\mu^{\rm mis}$ and ϵ_τ, for $m_\chi = 100$ GeV, $\sigma_p = 10^{-41}{\rm cm}^2$ and an exposure $M_{\rm det} N_y = 1$ Mton$\times$year.

for $\nu\bar{\nu}$: an efficiency of tau-events reconstruction $\epsilon_\tau \simeq$ 50-60% would allow to a clear signal detection with $\epsilon_e^{\rm mis} = \epsilon_\mu^{\rm mis} \simeq$ 5-9%. Alternatively, a reduction of $\epsilon_e^{\rm mis} = \epsilon_\mu^{\rm mis} \simeq 1\%$ level would be enough (for this benchmark case) to obtain a 5 σ detection with $\epsilon_\tau \simeq 40\%$.

Sensitivity to DM scattering cross section σ_p



Contours for $\varsigma = 1.64$, for a detector with exposure $M_{\rm det} N_y$ =1 Mton×year.
Dotted lines: limits without considering misidentification,
solid lines: ϵ_τ=40% and $\epsilon_e^{\rm mis}$=$\epsilon_\mu^{\rm mis}$=4%.

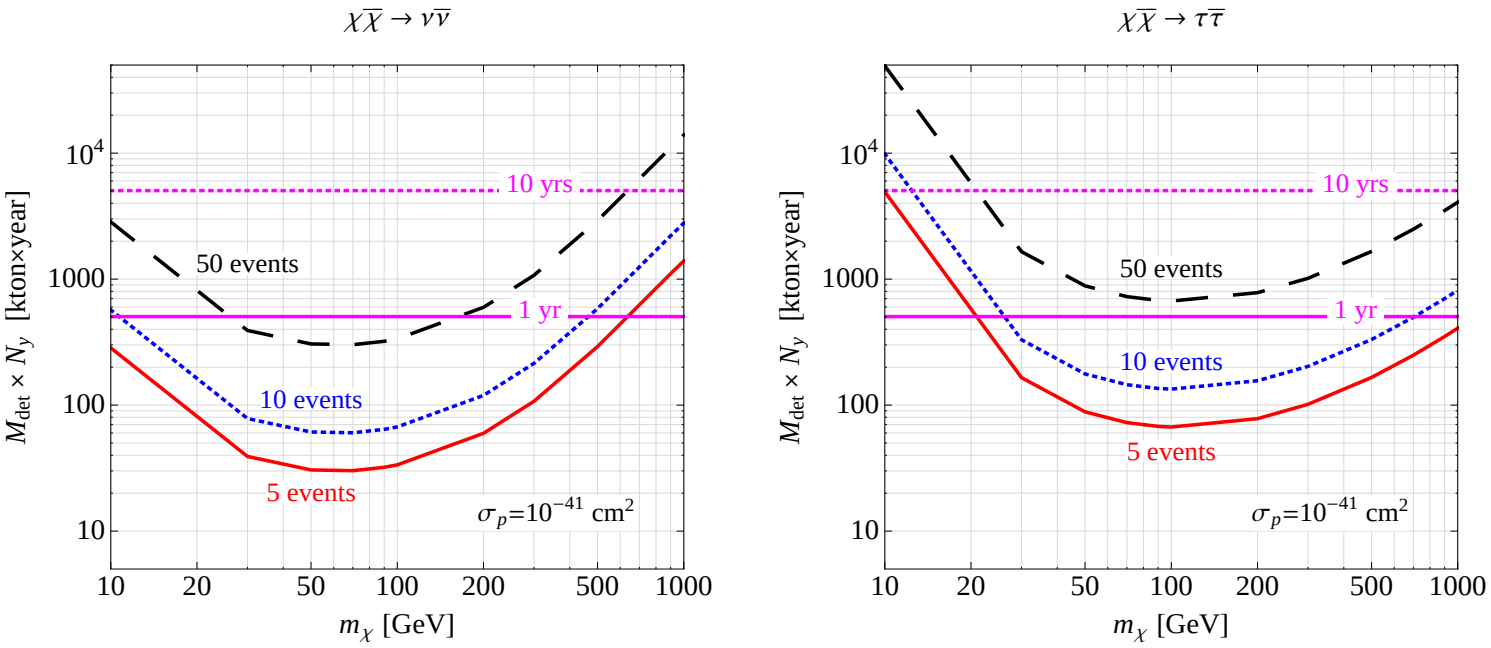
DAMA and CoGeNT direct detection experiments point toward a light DM candidate with $m_\chi \simeq 10$ GeV and $\sigma_p \simeq 10^{-42}$ cm^2 - 10^{-40} cm^2:
$\rightarrow \nu\bar{\nu}$: 9 - 900 hadronic events in 10 yrs HK
$\rightarrow \tau\bar{\tau}$: 1 - 50 hadronic events in 10 yrs HK

Conclusions

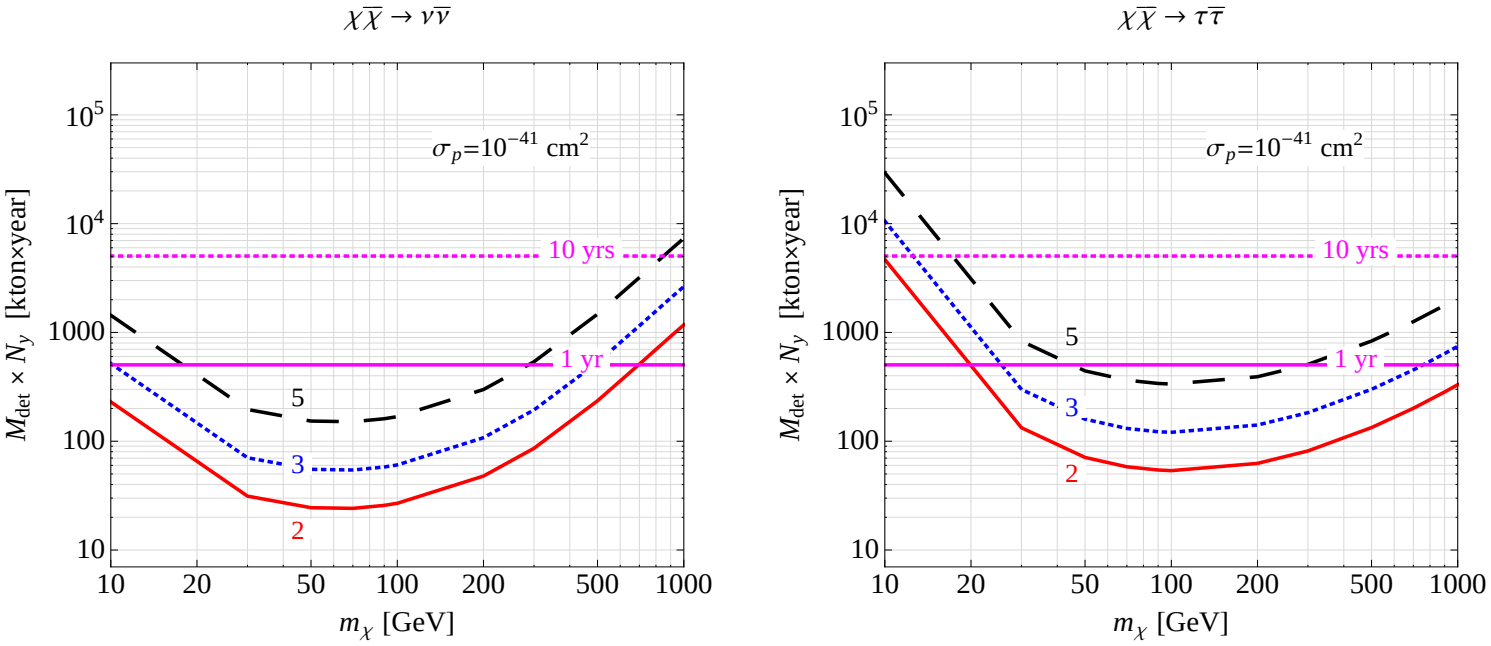
Possible new channel for DM searches at Cherenkov detectors
$\Rightarrow$ downward-going hadronic tau events:

- the downward-going ν_τ background is extremely small
- statistical methods to identify hadronic tau events
- several tens of events per year (depending on m_χ/BR_f) are potentially collectible in a Mton-scale detector, like Hyper-Kamiokande
- the main limitation to the downward-going tau neutrinos signal is the level of misidentification of NC/CC ν_μ e ν_e events, which need to be kept at level of percent
- a 5 σ significance discovery is potentially reachable for m_χ in the range from 20 to 300 GeV with 10 years of exposure, and for $\sigma_p = 10^{-41}$ cm^{-2} ($\epsilon_\tau = 40\%$, $\epsilon_e^{\rm mis} = \epsilon_\mu^{\rm mis} = 4\%$)
- a better performance will enlarge the 5 σ discovery region in the (m_χ, σ_p) plane

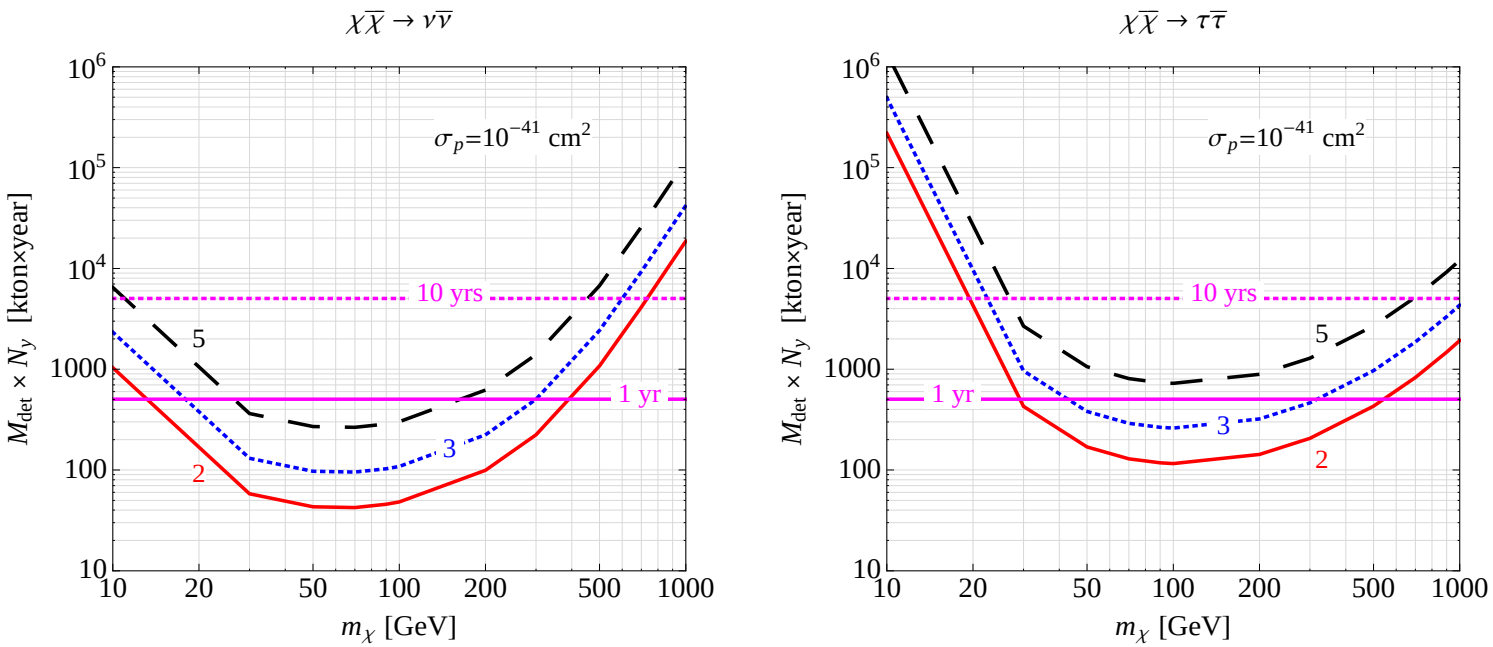
BACKUP SLIDES



For a Mton-scale detector, the expected number of down-going ν_τ signal events can reach the level of 50 or more, depending on the DM mass. For a prolonged exposure of a decade or more, more than a hundred of signal events is potentially under reach.



Full efficiency for the detection of tau hadronic events ($\epsilon_\tau = 100\%$) and no misidentification.



Efficiency of tau hadronic events $\epsilon_\tau = 70\%$ and misidentification of of electron and muon events $\epsilon_e^{\rm mis} = \epsilon_\mu^{\rm mis} = 1\%$.