# Dark Matter searches with the ANTARES neutrino telescope

## 20$^{\text{th}}$ Multidark Consolider Workshop


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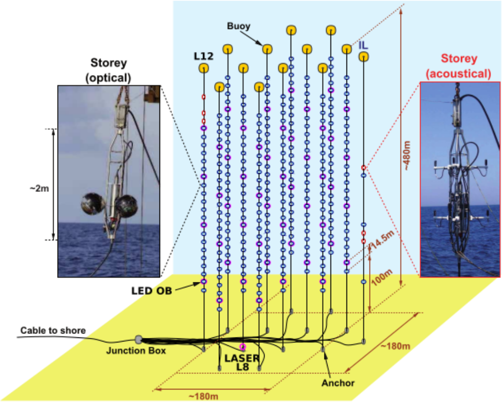
# ANTARES telescope

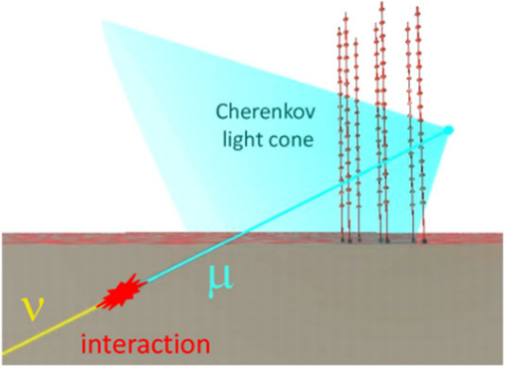
**ANTARES**: **A**stronomy with a **N**eutrino **T**elescope and **A**byss environmental **RES**earch.




ANTARES: The first undersea neutrino telescope

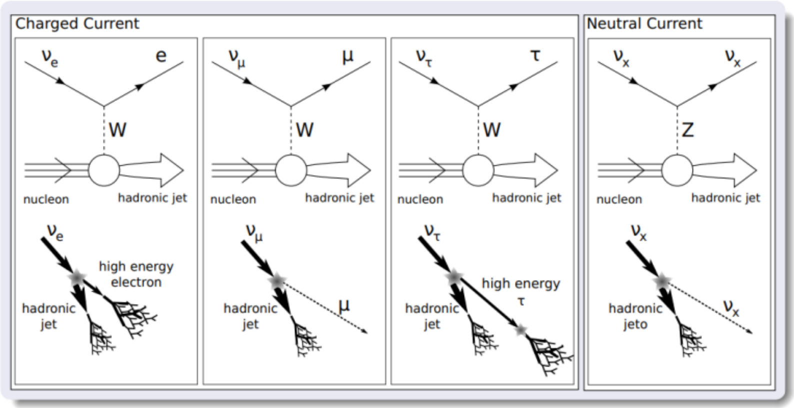
# Detection principle

ANTARES detected the Cherenkov light produced in sea water from secondary charged particles which originate in the interactions of neutrinos with the matter around the instrumented volume.



# Type of events

Two types of event signatures can be detected in neutrino telescopes: tracks and showers.



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# DM hypothesis

Weakly interacting massive particles (WIMPs) are the most studied candidates for Dark Matter particles.

The self-annihilation of WIMPs may produce neutrinos:

- Through Standard Model mediators:

$$\chi\chi \rightarrow b\bar{b}/W^{-}W^{+}/\tau^{-}\tau^{+}/\mu^{-}\mu^{+}/\nu\bar{\nu} \rightarrow \nu\bar{\nu}$$

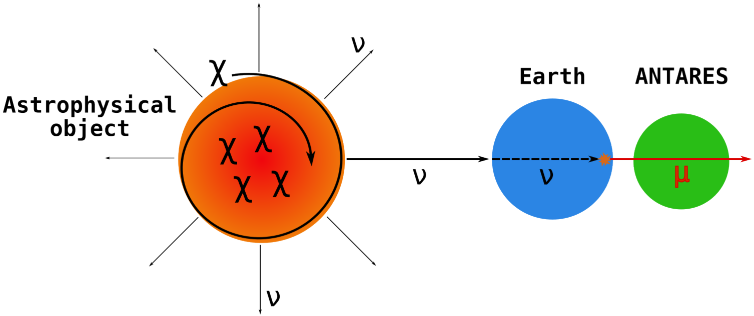
- Through metastable mediators, such as new gauge bosons (Secluded Dark Matter scenario):

$$\chi\chi \rightarrow \phi\phi \rightarrow \mu^{-}\mu^{+}/\nu\bar{\nu} \rightarrow \nu\bar{\nu}$$

# DM indirect detection in ANTARES

Competitive upper limits to thermally-averaged WIMP-WIMP cross section (for extended sources like the Galactic Centre) and to neutrino flux and WIMP-nucleon cross section (for point-like sources like the Sun or the Earth).

No evidence of neutrino flux from DM annihilation has been found so far.



# ANTARES DM analysis

WIMP annihilation in the Galactic Centre

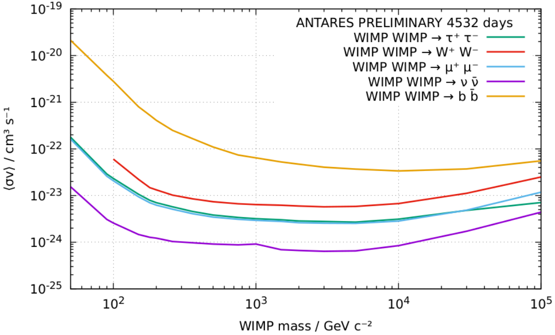



Figure: Upper limits at 90% confidence level on the thermally averaged cross section for pair annihilation of WIMPs resulting to neutrinos. For low WIMP masses, previous results also contain a dedicated reconstruction fit for events reconstructed on single-line data. (Figure taken from: *ANTARES Collaboration, S.R. Gozzini, PoS(ICRC2023) 1375*)

# ANTARES DM analysis

## WIMP annihilation in the Galactic Centre

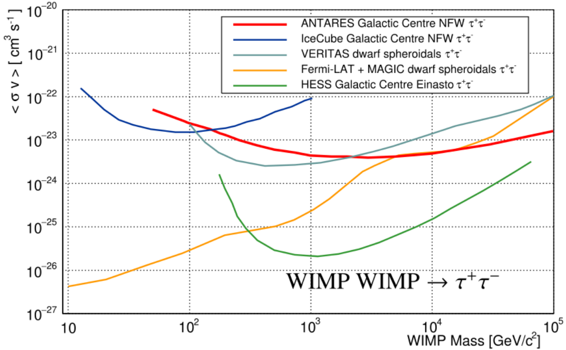



Figure: Previous results (11 years of data) compared with other experiments (at 2020). (Figure taken from: *ANTARES Collaboration. Search for dark matter towards the Galactic Centre with 11 years of ANTARES data*)

# ANTARES DM analysis

WIMP annihilation in the Sun

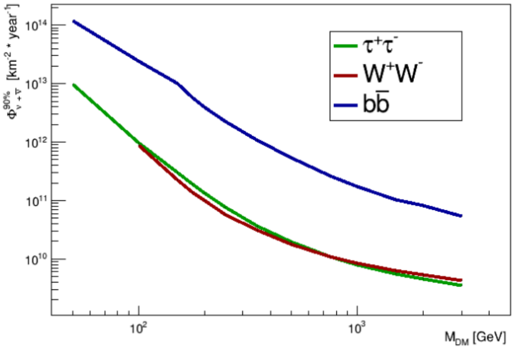



Figure: Upper limits on the flux for the indirect search of dark matter towards the Sun, using ANTARES data from 2007 to the end of 2019. (Figure taken from: *C. Poirè, PhD thesis*)

# ANTARES DM analysis

WIMP annihilation in the Sun

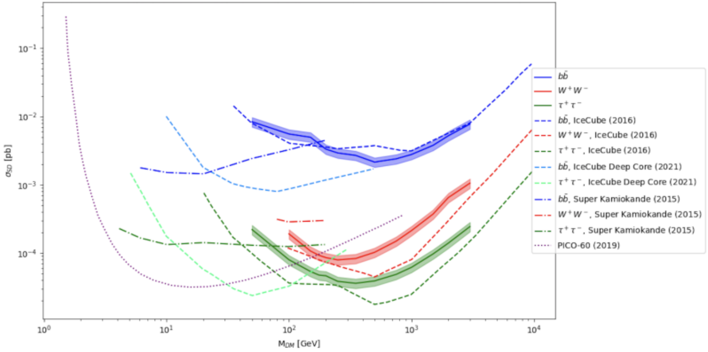



Figure: Limits on the spin-dependent WIMP-nucleon scattering cross section as a function of WIMP mass for the $b\bar{b}$ (blue), $\tau^-\tau^+$ (green) and $W^-W^+$ (red) channels. Limits given by other experiments are also shown: IceCube, PICO-60, SuperKamiokande. (Figure taken from: *C. Poirè, PhD thesis*)

# ANTARES DM analysis

Secluded WIMP annihilation in the Sun

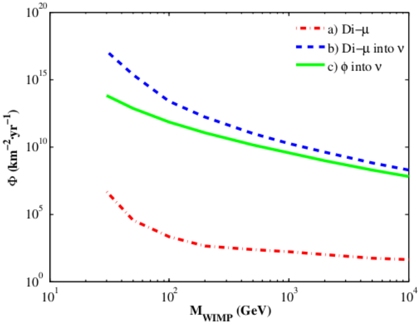



Figure: Sensitivity, expected 90% confidence limit, for DM annihilation in the Sun for three SDM scenarios with the data recorded by ANTARES between 2007 and 2012. (Figure taken from: *S. Adrián-Martínez, et al. A search for Secluded Dark Matter in the Sun with the ANTARES neutrino telescope.*)

# ANTARES DM analysis

Secluded WIMP annihilation in the Sun

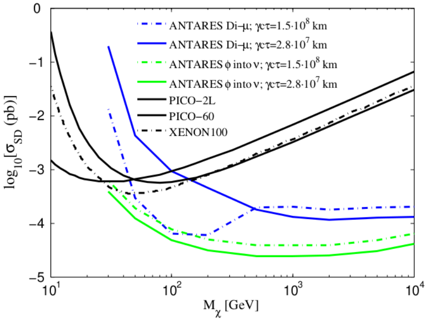



Figure: ANTARES 90% CL upper limits on WIMP-nucleon spin-dependent cross section as a function of WIMP mass. Two favourable mediator lifetimes are considered. The bounds in 2016 from PICO, LUX and XENON are also shown. (Figure taken from: *S. Adrián-Martínez, et al. A search for Secluded Dark Matter in the Sun with the ANTARES neutrino telescope.*)

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# NNFit

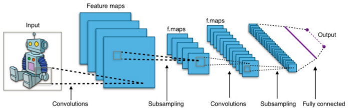
- NNFit is the name given to a collection of Machine Learning algorithms that we have developed and trained with Monte Carlo simulations. It reconstructs neutrino properties of so-called Single-Line (SL) events.

- These algorithms are supervised methods and they combine Deep Neural Networks (NNs) and dimensionality reduction approaches.

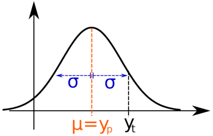
- NNFit is subdivided in two: NNFitTrack and NNFitShower. The first has been trained with Charged Current neutrino-(anti)muon simulations ($\nu_{\mu}^{CC}$), while the second has been trained with neutrino-(anti)electron and Neutral Current neutrino-(anti)muon simulations ($\nu_{e}^{CC}$, $\nu_{e}^{NC}$, $\nu_{\mu}^{NC}$).

# NNFit main algorithms

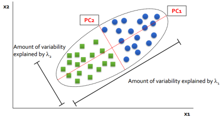
- Deep Convolutional Networks (DCNs) $\Longrightarrow$




- Mixture Density Networks (MDNs) $\Longrightarrow$



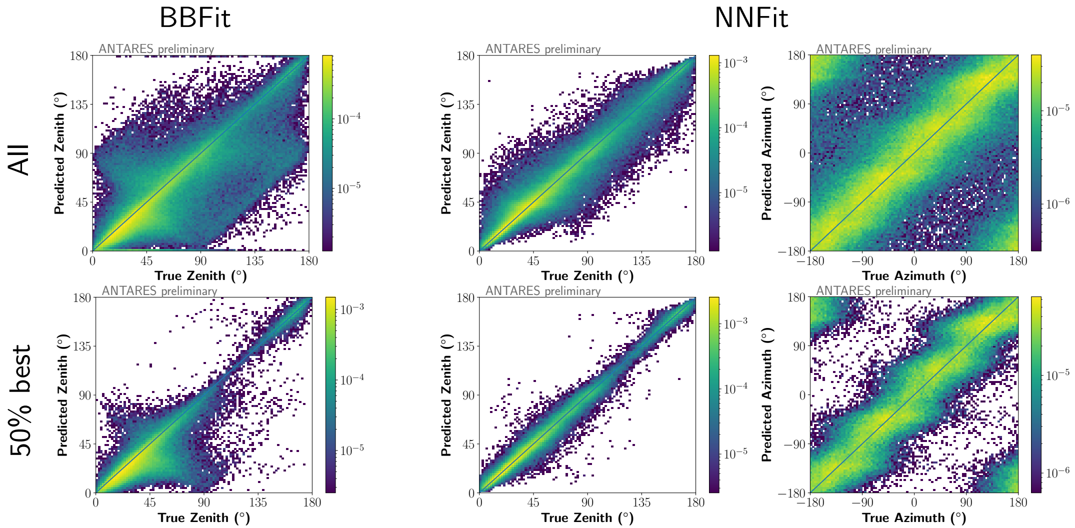

- Principal Component Analysis (PCA) $\Longrightarrow$



# Parameters reconstructed

- NNFitTrack:
  - Direction: Angles ($\theta$, $\phi$) and their respective estimated error ($\sigma_\theta$, $\sigma_\phi$).
  - Closest point of the track to the detector line: In terms of horizontal distance and vertical point ($R_c$, $Z_c$) and their respective estimated error ($\sigma_{R_c}$, $\sigma_{Z_c}$).
  - Energy of the **muon**: In logarithmic scale and its error ($\log_{10}(E/[GeV])$, $\sigma_{\log_{10}(E/[GeV])}$).
- NNFitShower:
  - Direction: Angles ($\theta$, $\phi$) and their respective estimated error ($\sigma_\theta$, $\sigma_\phi$).
  - Interactions vertex point: In terms of horizontal distance and vertical point ($R_v$, $Z_v$) and their respective estimated error ($\sigma_{R_v}$, $\sigma_{Z_v}$).
  - Energy of the **neutrino**: In logarithmic scale and its error ($\log_{10}(E/[GeV])$, $\sigma_{\log_{10}(E/[GeV])}$).

# Direction reconstruction: Results

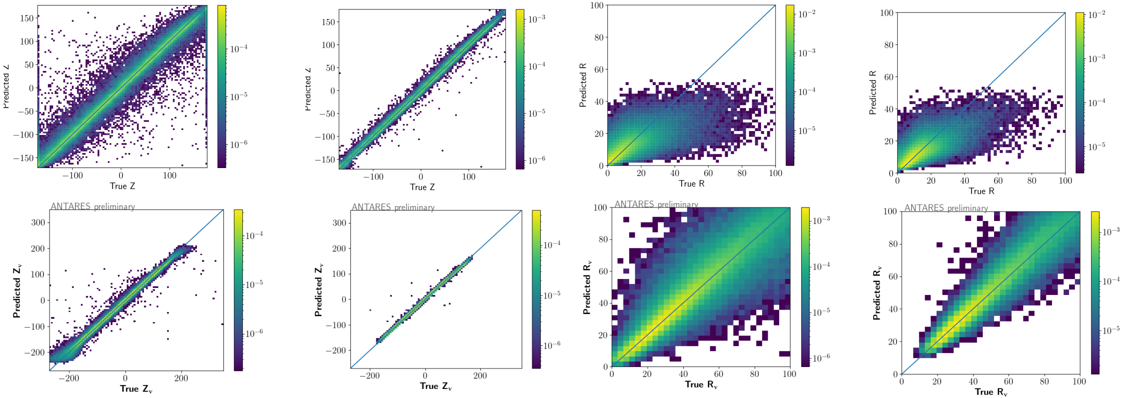


# Closest point of the track / Vertex point of the shower: Results

All events | 50% lowest $\sigma_Z$ | All events | 50% lowest $\sigma_R/R$

NNFitTrack

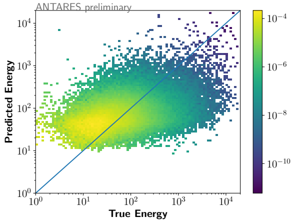
NNFitShower

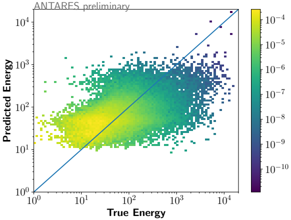


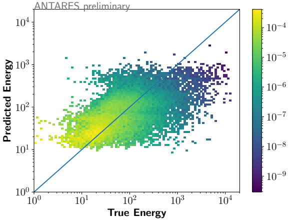
# Energy results

All events | 50% lowest $\sigma_{\log_{10}(E)}$ | 25% lowest $\sigma_{\log_{10}(E)}$

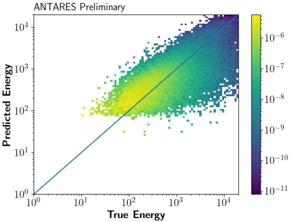
NNFitTrack

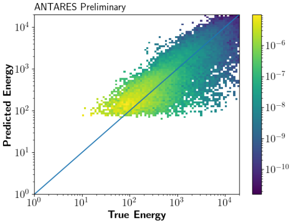


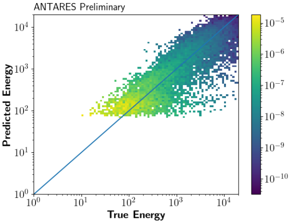




NNFitShower



# DM search method

We performed a binned dark matter search towards the Sun with a subset of the ANTARES data (from 2008 to 2017).

We use an asymmetric Region of Interest (RoI) because the nature of our NNFit direction reconstruction is also very asymmetric. The RoI is defined by a *radius* in the zenithal coordinate ($R_\theta$) and a *radius* in the azimuthal coordinate ($R_\phi$).

We need to compute the Acceptance and the Background for several set of cuts to obtain the average upper flux limit.

In order to compare the results, we made the study with BBfit SL for the same dataset.

# Optimization parameters

We optimize three parameters:

- $R_\theta$ spans from 3° to 15° in steps of 1°.
- $R_\phi$ spans from 20° to 50° in steps of 10°.
- $\sigma_\Omega = \sqrt{\sin^2(\theta) \cdot \sigma_\phi^2 + \sigma_\theta^2}$ (quality parameter) spans from 5° to 35° in steps of 2°.

In order to compare with Bbfit-SL, we make the same studio with its reconstruction:

- $\chi^2$: This is used as quality parameter. It spans from 0,6 to 1,2 in steps of 0,1.
- $R_\theta$: This defines the RoI, which is actually a band. It spans from 4° to 12° in steps of 1°.

# Effective Area and Acceptance

First, we compute the Effective Area with a band approach. For that, we apply these cuts:

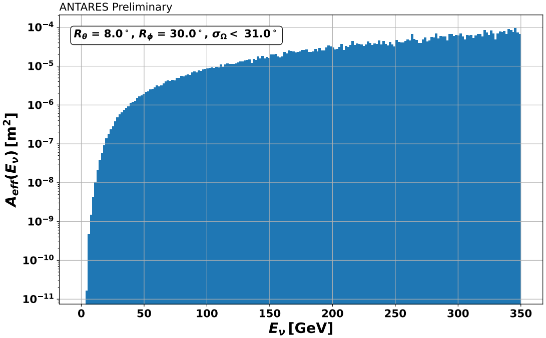
- Pre-cuts: Only SL events, cuts used to train energy, $\theta_{rec} < 90^\circ$ and $\sigma_{\log_{10}(E)} < 0.5$
- Quality cut: $\sigma_\Omega < \sigma_{\Omega,\,\mathrm{max}}$
- Cut on Zenith band: $|\theta_{sun} - \theta_{true}| < R_\theta$
- Cut on RoI: $|\theta_{rec} - \theta_{true}| < R_\theta$ and $|\phi_{rec} - \phi_{true}| < R_\phi$
- Cut on Energy: $E_{\mu,rec} < M_{WIMP}$ and $E_{\mu,rec} > 10\ GeV$

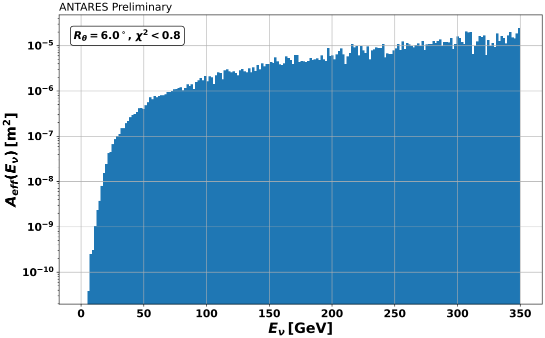
Then, the Acceptance is computed as an averaged convolution of each annihilation energy spectrum with the $A_{eff}$. The spectra have been computed with WimpSim.

# Effective Area

The contribution of each event that passes the cuts is:

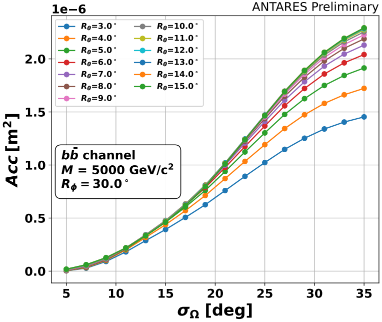
$$\frac{\omega_{2,i}}{k \cdot (E_M^{1-\Gamma} - E_m^{1-\Gamma})} \times \frac{(1-\Gamma)}{F \cdot I_\theta \cdot E_\nu^\Gamma}$$

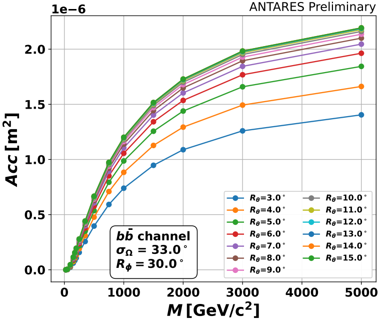


# Acceptance

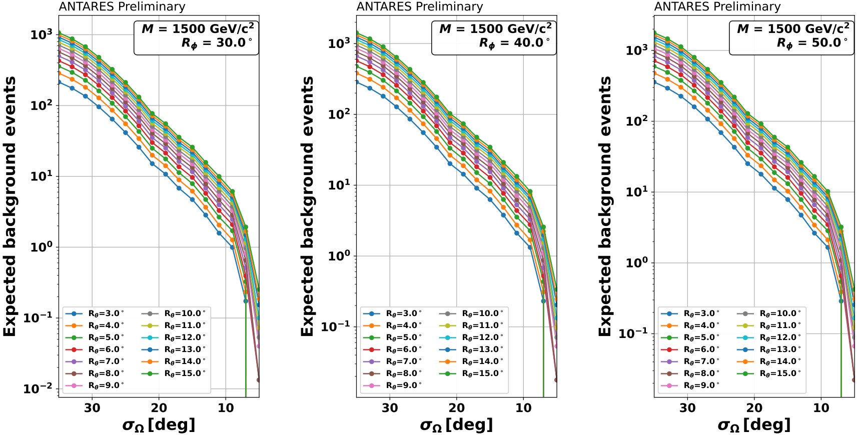
$$Acc = \frac{\sum_{j=\nu,\bar{\nu}} \int_0^{M_{WIMP}} A_{eff}(E_j) \cdot \Phi(E_j) \cdot \mathrm{d}E_j}{\sum_{j=\nu,\bar{\nu}} \int_0^{M_{WIMP}} \Phi(E_j) \cdot \mathrm{d}E_j}$$



# Background

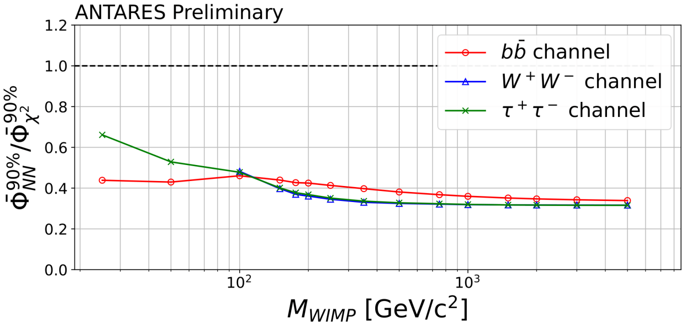
We scramble the data 100 times and renormalize by 5, so we gain a factor 20 in the Effective time: 0.5479 *years* $\times$ 20 $\simeq$ 10.96 *years*



# Flux upper limits

According to the MRF approach, we select the set of cuts for every channel and mass of the WIMP that gives the best average flux upper limit:

$$\bar{\phi}^{90\%}_{\nu+\bar{\nu}} = \frac{\bar{\mu}^{90\%}}{Acc(M_{WIMP}) \cdot T_{eff}}$$



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# Conclusions

- ANTARES has proven to be very competitive in the search for Dark Matter compared to other detectors and has laid the groundwork for its successor: KM3NeT.

- With our latest work we hope to improve the results at low energies in the final ANTARES analysis.

# Thanks for your attention!

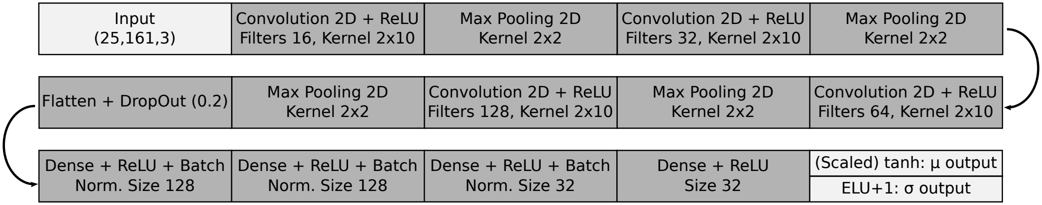
Questions or comments?

# BACK UP

# Direction and closest point reconstruction: Network architecture

We combine a Deep Convolutional Network (DCN) with a Mixture Density Network (MDN). The latter allow us to predict an error estimation ($\sigma_\mu$) of the reconstructed property ($\mu_{rec}$) using this Loss Function:

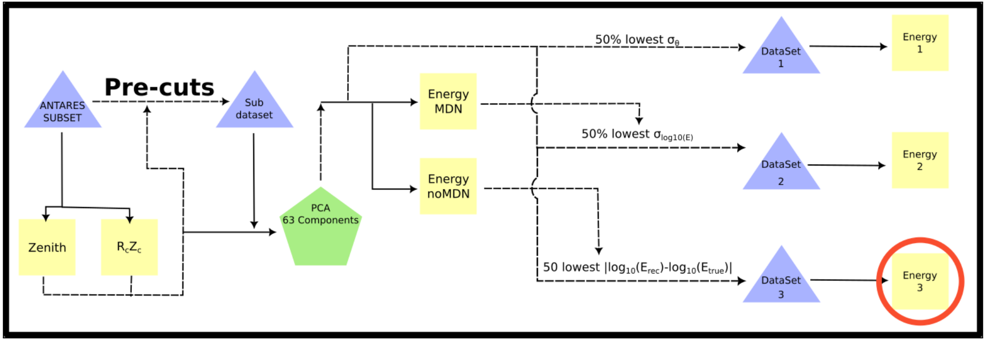
$$\mathcal{L} = -\ln(\text{likelihood}) = \ln(\sigma_\mu \sqrt{2\pi}) + \frac{1}{2}\left(\frac{\mu_{true} - \mu_{rec}}{\sigma_\mu}\right)^2$$




García-Méndez, et al. Deep Neural Networks for Single-Line Event Direction Reconstruction in ANTARES

# Energy reconstruction method

We made a selection of the subset we used to train the other networks, applying some cuts to ensure that we are working with events which track is close to the line and that their reconstruction is of good quality. These cuts will be also applied in physics searches as pre-cuts. This will reduce the background while keeping the best reconstructed events.



# PCA components selection

To obtain the number of components, we use the elbow rule: