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CYGNO Experiment

# Discovering Supernovae-produced Dark Matter with directional detector


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Discovering supernova-produced dark matter with directional detectors

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Supernovae can produce vast fluxes of new particles with masses on the MeV scale. When the new particle becomes diffusively trapped within the supernova, the escaping flux exhibits an order-one spread in velocities. Overlapping emissions from galactic supernovae produce an overall flux at Earth that is approximately constant in time. However, this flux is highly anisotropic and is steeply peaked towards the Galactic center. This is in contrast with the cosmological abundance of dark matter which, due to the rotation of the Galaxy, appears to come from the direction of the Cygnus constellation. In this paper, we demonstrate the need for a directional detector in order to discriminate between a signal from a cold cosmological abundance of GeV-scale WIMPs and a signal from a hot population of supernova-produced MeV-scale dark matter. We then discuss the discovery prospects for a wide variety of proposed directional experiments.


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# Goal of the work

- When (If) Dark Matter will be discovered, which model will describe the data?


- We want to show that directionality plays a major role in the **discrimination** of models, reducing the number of events needed to pick among them

The toy–model for SN DM will be used as
an alternative to the WIMP

# Recoil Spectra and Kinematics

- The first step is to calculate the expected spectra of the two models in our hypothetical detector.

## Kinematics

The formula of the recoil momentum of a nucleus *A*, hit by a particle *X* with momentum $p_0$ is

$$q=\frac{m_A\left(\sqrt{p_0^2+m_X^2}+m_A\right)p_0\cos\theta_r}{\left(\sqrt{p_0^2+m_X^2}+m_A\right)^2-p_0^2\cos^2\theta_r}$$

where $\theta_r$ is the recoil angle

## Cross section

To obtain the differential cross section in the rest frame*

$$\frac{dR}{dE\,d\Omega}=A\int\frac{S(q)}{q_{max}^2}\delta(\cos\theta-kinematics)f(\vec{v})d^3v$$

*S(q):* form factor
*q:* transferred momentum
*θ:* recoil angle
*f:* distribution of velocities

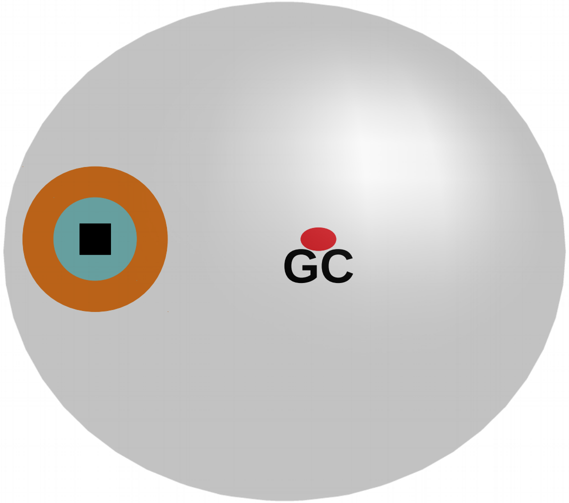
* P. Gondolo, *Recoil momentum spectrum in directional dark matter detectors*, 2002

# Recoil Spectra Approximations

- In general the detector is on the Earth which is performing a very complex motion in the Galactic reference frame

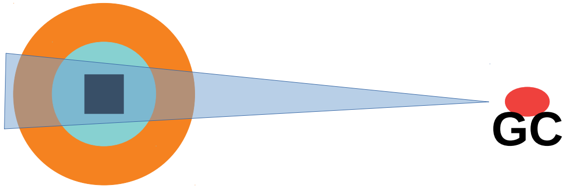
we assume the detector inside the Earth which is inside the Sun

WIMP




Particles moving at compatible speed as the Sun:
Sun motion is **included**

SNDM




Relativistic particles, also Sun motion is **neglected**

- In both cases the final spectra will depend on **target element, DM masses**

# Recoil Spectra Approximations

- We want to analyse different combination of parameters in the study of the recoil spectra

**Theoretical parameters**

We want to see what happens with high and low mass of both models:

WIMP 1–100 Gev/$c^2$

SNDM 10–60 MeV/$c^2$

**Target**

We want to compare directional detectors (like CYGNO) with other major non directional detectors

He, F, Xe (Ar, Ge, Si)

- In the following slides the parameters chose as an exemple are

| **WIMP mass** | **SNDM mass** | **Target** |
|---|---|---|
| 100 Gev/$c^2$ | 48 Mev/$c^2$ | F (if not specified) |

# WIMP Recoil

- In the WIMP model, DM distribution is approximated by a Maxwell–Boltzmann distribution

$$f(\vec{v}) = B \cdot e^{-\frac{v^2}{v_s^2}}$$

$V_s$=230 km/s

- Due to the non relativistic motion of WIMPs, the recoil momentum can be approximated as

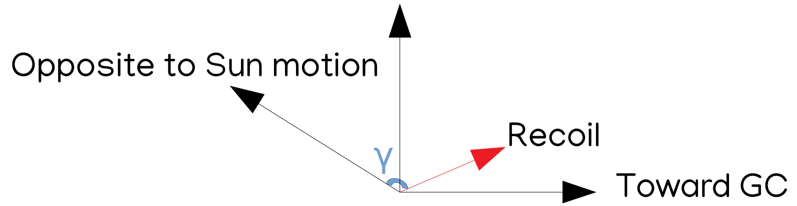
$$q = 2\mu v \cos\theta$$

μ: reduced mass of the nucleus and WIMP particle
θ: angle of recoil of nucleus if WIMP is coming from z-axis

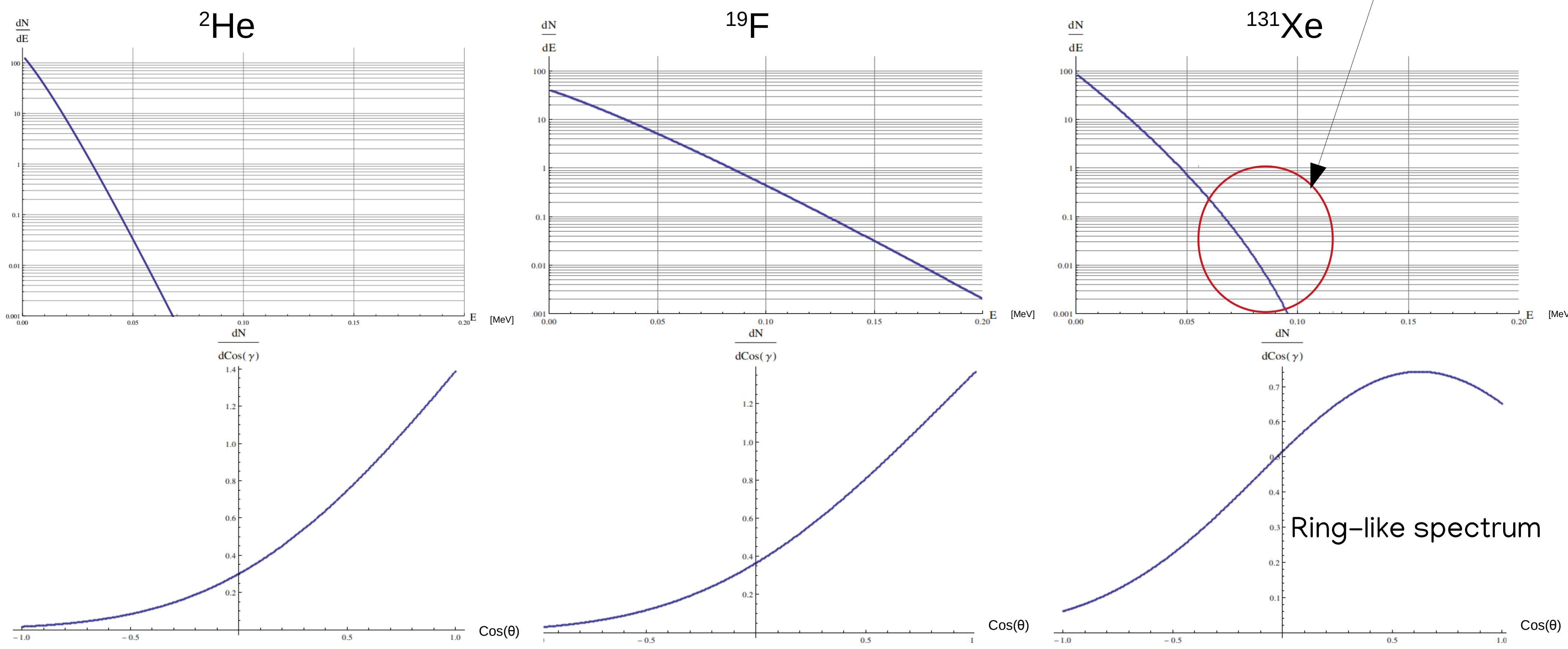
- The differencial rate can be calculated taking into account all the coordinate transformations

$$\frac{dR}{dE d\cos\gamma} \propto S(q) \cdot e^{\frac{-\left(\frac{\sqrt{2 m_A E}}{2\mu} - v_{lab}\cos\gamma\right)^2}{v_s^2}}$$

$v_{lab}$: velocity of the Sun around the Galactic Centre



- Using a WIMP mass of 100 GeV/$c^2$



# SNDM Recoil

- In the SNDM model DM distribution is approximated by a Fermi–Dirac distribution

$$f(\vec{p}) = \frac{B}{e^{\frac{\sqrt{p^2+m_X^2}}{T}}+1}$$

T: temperature of decoupling in SN, given by model

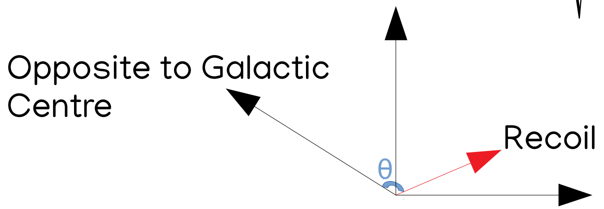
- Due to the relativistic motion of SNDM particles, the recoil momentum can be approximated as

$$q = 2p\cos\theta$$

θ: angle of recoil of nucleus if SNDM particles are coming from z–axis

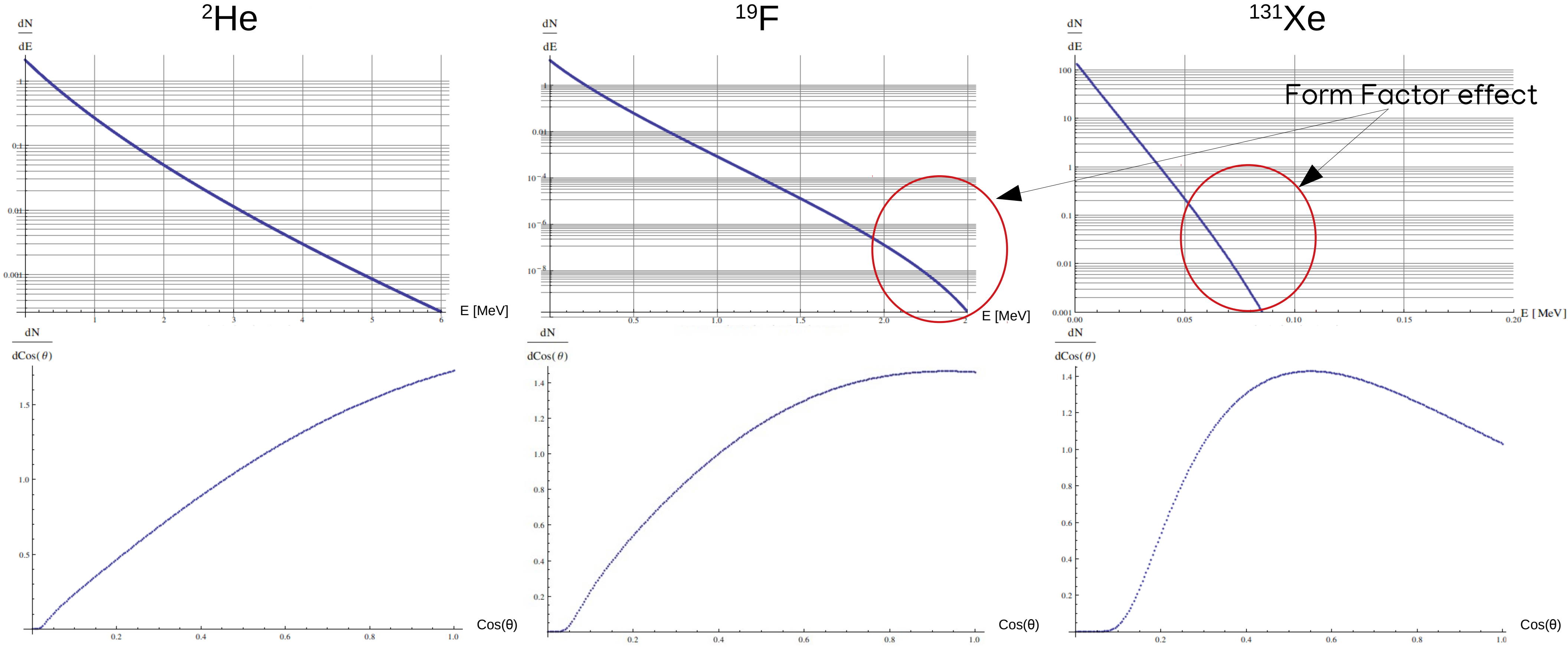
- The differencial rate can be calculated considering the SNDM particle as a beam from the Galactic Centre

$$\frac{dR}{dE d\cos\theta} \propto \int S(q)\cdot\delta\left(\cos\theta - \frac{q}{2p}\right)\cdot\frac{p}{m_X}\frac{1}{\sqrt{1+\frac{p^2}{m_X^2}}} f(p)\,dp$$



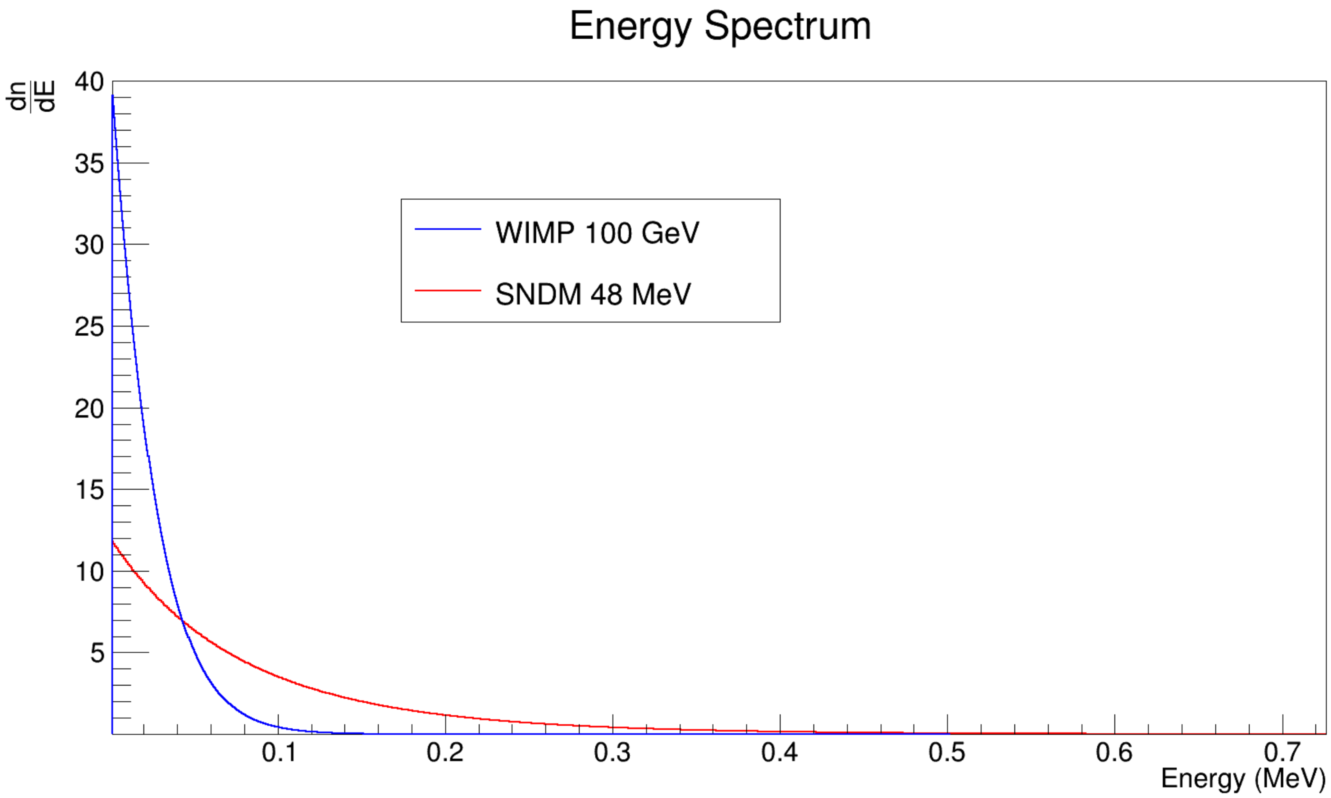
# SNDM Recoil Spectra

- Using a SNDM mass of 48 MeV/c$^2$ and a corresponding model temperature of 9.7 MeV/c$^2$

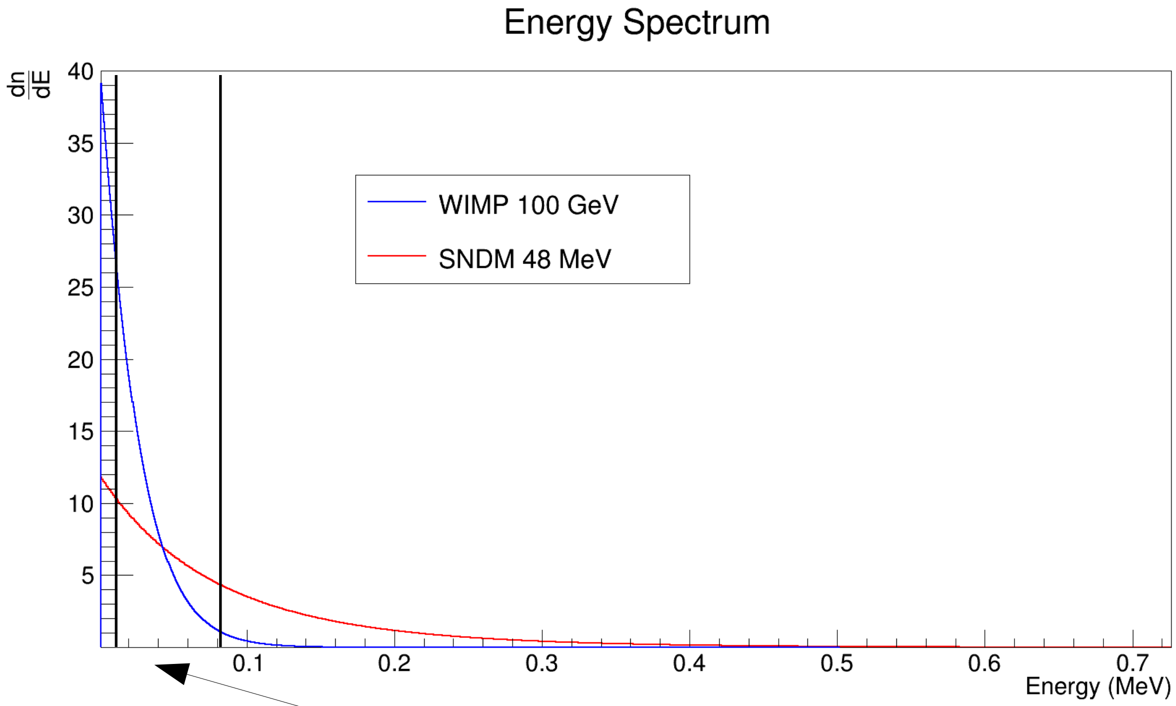


# Energy Spectra Comparison

- The energy spectra are independent of the reference system, so they can be immediately Compared. Fluorine was chosen as test element.



# Energy Spectra Comparison




- A better optimization of the **theoretical parameters** can make the spectra adhere more to each other

  ↓

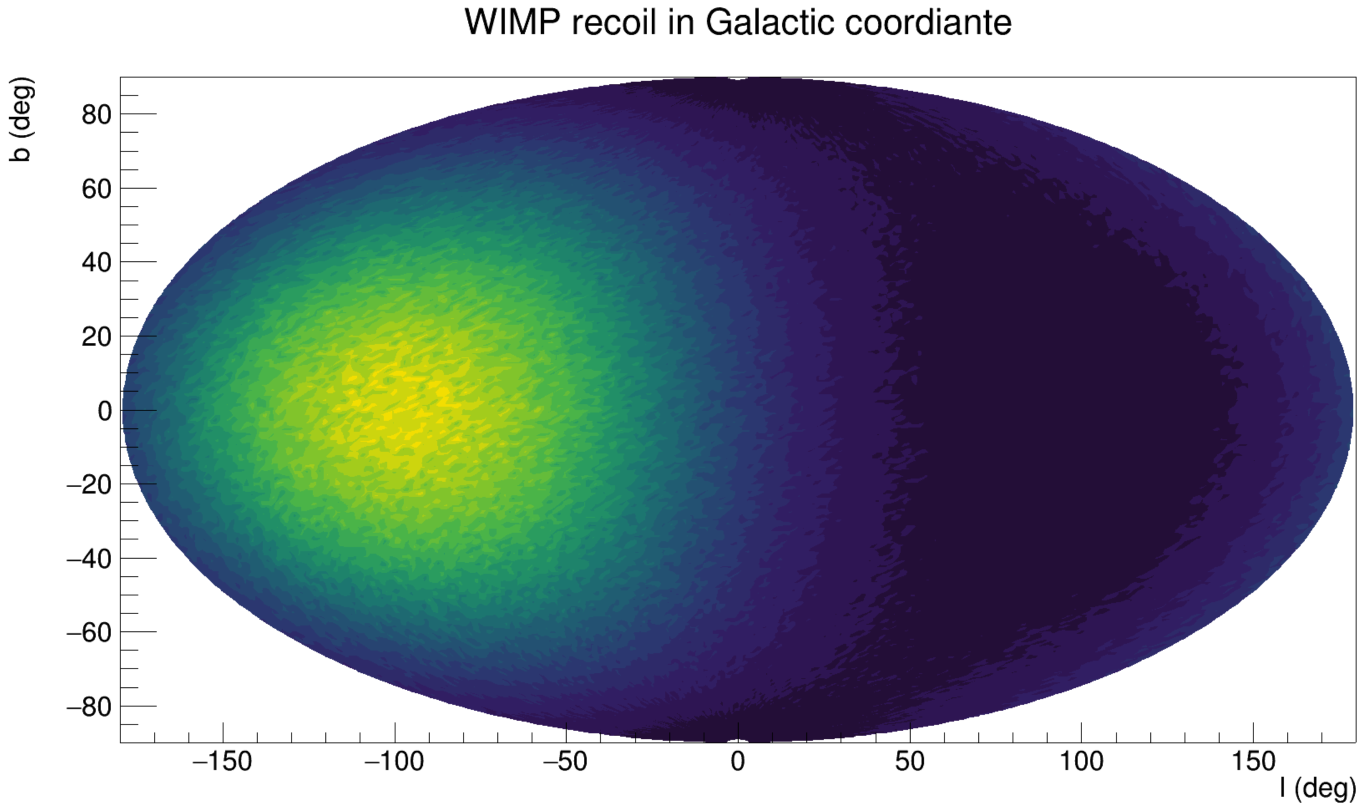
  Under study

- **Fluorine** was chosen as an intermediate mass target. Increasing the target mass, the spectra tends to be more alike

- In the discrimination power of the two models, the **energy region of interest** chosen by each experiment plays a great role

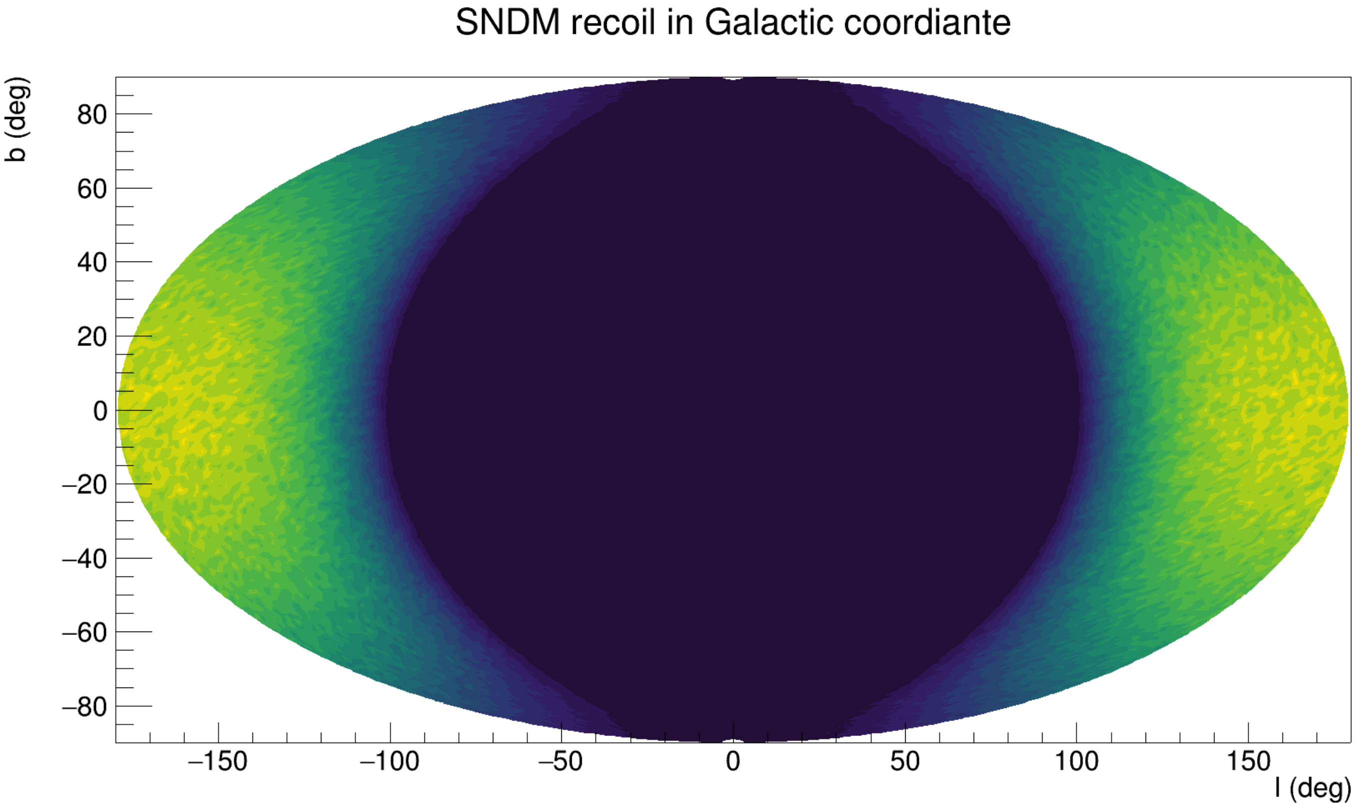
# WIMP Galactic Angular Spectrum

- The angular distribution of WIMPs has to be transformed to the Galactic coordinates



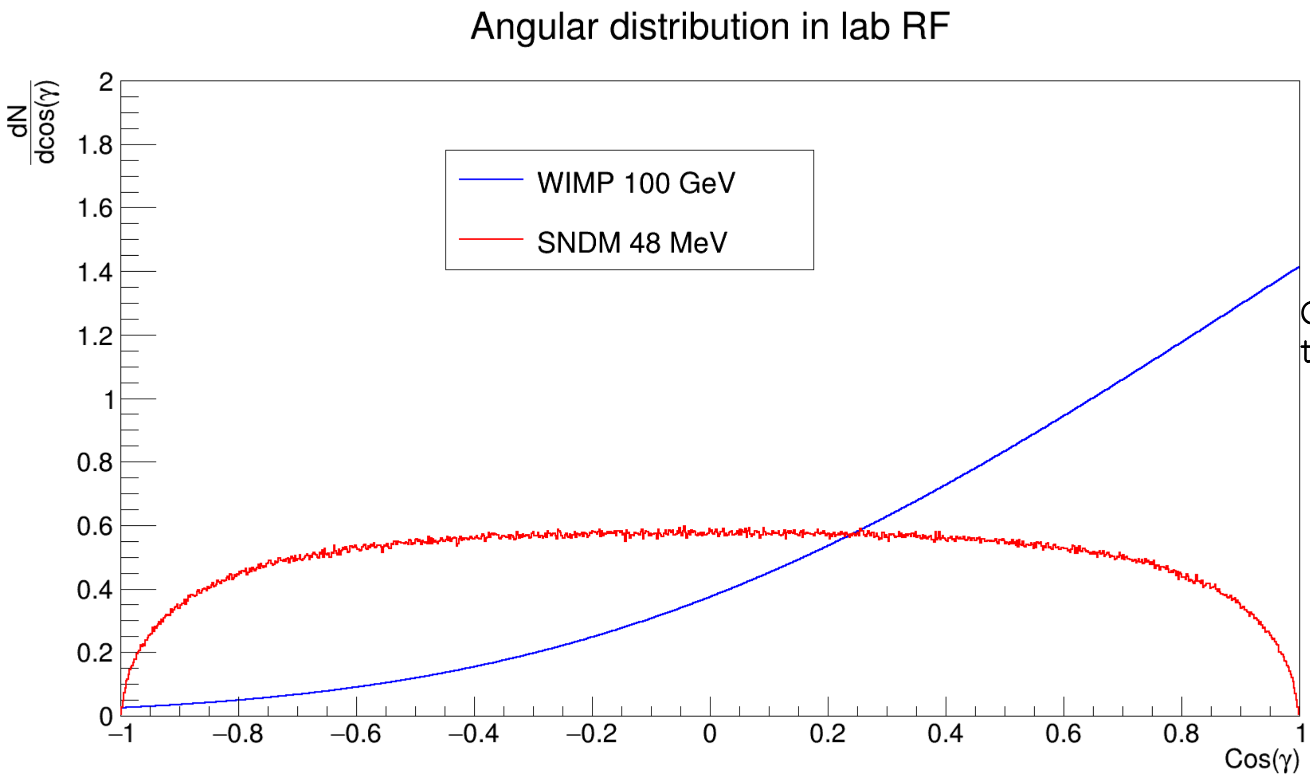
# SNDM Galactic Angular Spectrum

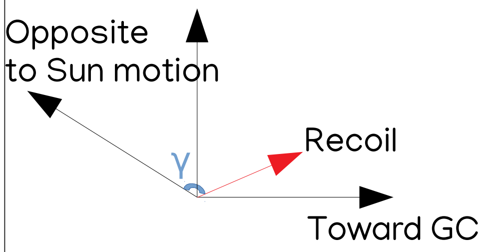
- The angular distribution of SNDMs has to be transformed to the Galactic coordinates



# Angular Spectra Comparison

- To compare the two distribution superimposed, the SNDM is shown in the same reference system as the WIMP one



# Statistical Analysis

The next step is to determine the number of events needed to discriminate among the models in the different data distributions

How?

**Loglikelihood method**

Builds the likelihood distribution of WIMP recoil spectra and looks at how many events one need from the other model to be sure the events do not belong the WIMP model

**Statistical test (Neumann–Pearson, Fisher–Discriminant)**

Creates a new variable, function of the data, to generate more separated distributions in order to discriminate better the models

# Statistical Analysis with Likelihood

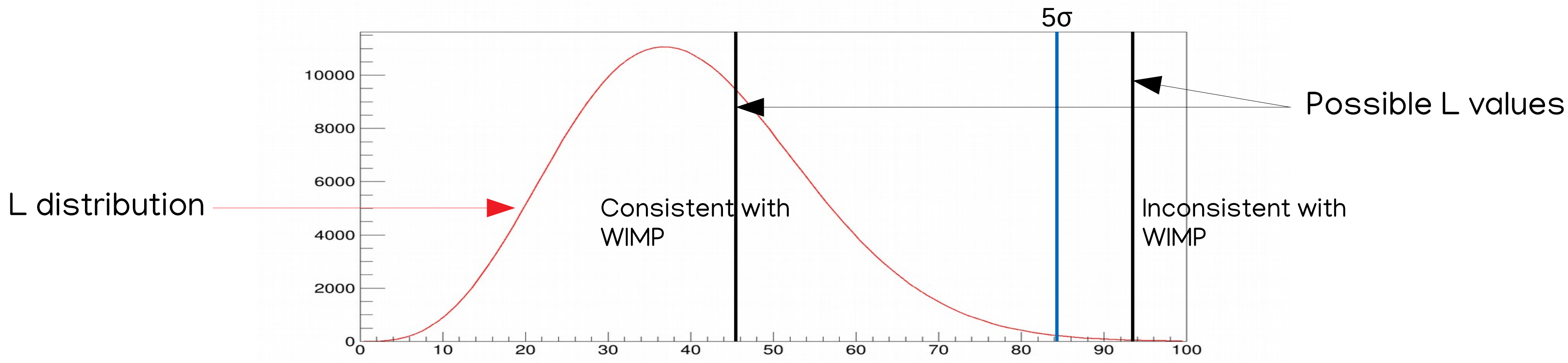
- We divide the spectra in bins and we create the distribution of the variable

$$L=\prod_{i=1}^{N_{bin}}\frac{\nu_i^{n_i}}{n_i!}e^{-\nu_i}$$

$\nu_i$: expected counts in bin i
$n_i$: actual counts in bin i

extracting $N_{events}$ randomly events from the WIMP one.

- Then, one extracts the same number of events from the SNDM spectrum obtaining an L value. This must be checked to see if it is found more or less probable then the p-value of 5σ.

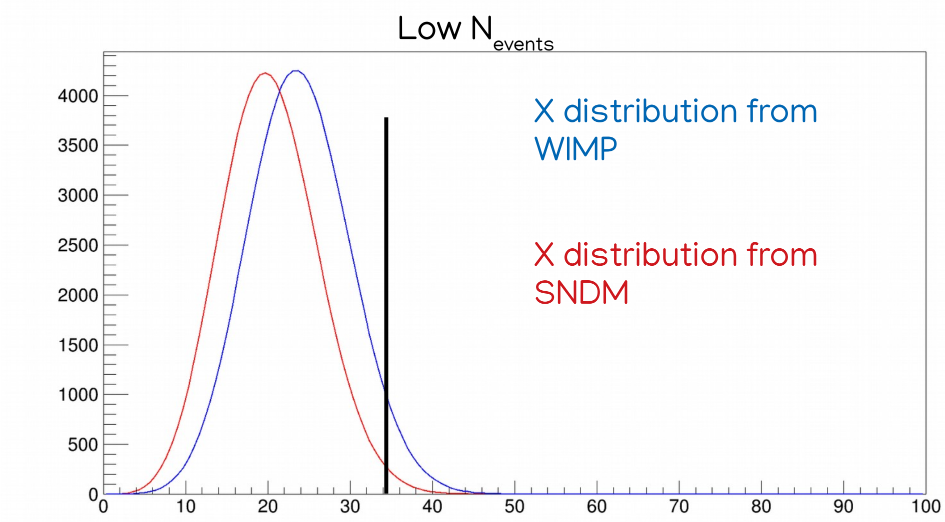


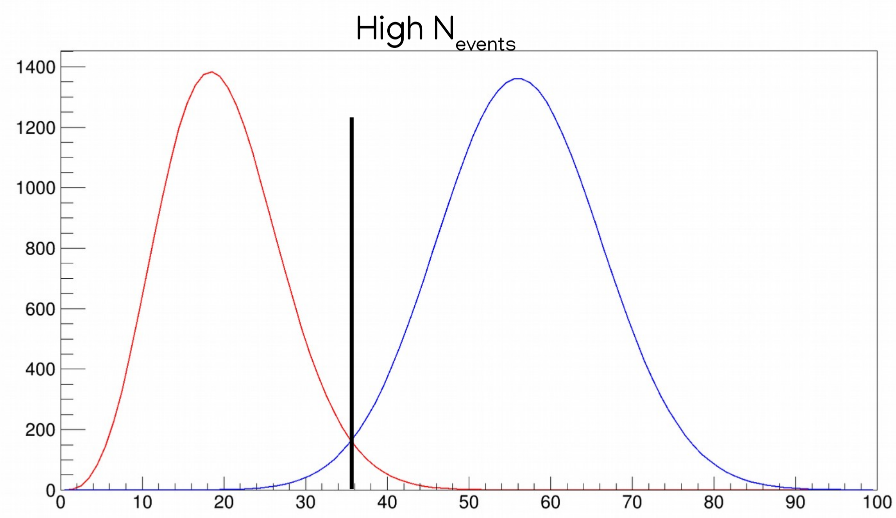
# Statistical Analysis with other Test

- A new variable must be created from data $X = F(N_{events}, \vec{x}_i)$

  so that the probability distributions of X using simulated WIMP data or SNDM data are well separated.

  The goal is to find the $N_{events}$ that allow to determine a threshold on the X to choose the belonging spectrum, minimizing type I and II errors.




- Statistical variables to try are Neumann-Pearson or to be obtained via Fisher discriminant

# Conclusions

- After the discovery of some Dark Matter events, it will be of great importance to understand which model is better suiting data and directionality can play a fundamental role.

- In this work, the WIMP model is compared with one based on the emission of dark fermions from SN Explosions.

- The recoil spectra in energy and direction were calculated and superimposed in the same reference system.

- A statistical test to determine the number of events needed to discriminate among the models is under study and development.