PhD seminar

Searches for dark matter as WIMPs and Kaluza-Klein axions with the MIMAC detector

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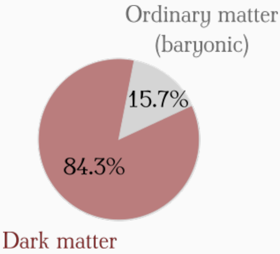
Under the supervision of Daniel Santos

- 18th of March 2021 -

The dark matter problem

- There are multiple observations of gravitational effects at multiple scales that can be explained if an unknown matter populates the Universe
  $\Longleftrightarrow$ Dark matter hypothesis
- The detection of a dark matter particle would be a **crucial discovery** for the understanding of the Universe



- Matter content of the Universe -
Data from *Planck Collaboration*, **2018**, 1807.06209

What is dark matter made of?

- Particles of the Standard Model are ruled out
- A candidate must be massive, no electric charge, no color, stable or long-lived
  $\Longrightarrow$ Zoo of candidates!

With MIMAC we search for:

- WIMP $\leftarrow$ The most studied candidate
- Kaluza-Klein axion $\leftarrow$ A pretty new theory (2000's)

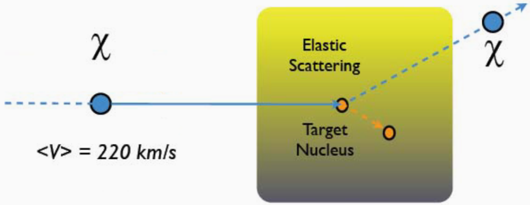
Plan

WIMP	– Strategy of detection – The MIMAC detector – Comimac
Directionality at high gain	– Statement – Simulations
Kaluza-Klein axions as a probe for extra dimensions	– Theoretical aspects – Experimental aspects – Model revision

WIMP

WIMP = Weakly Interacting Massive Particle

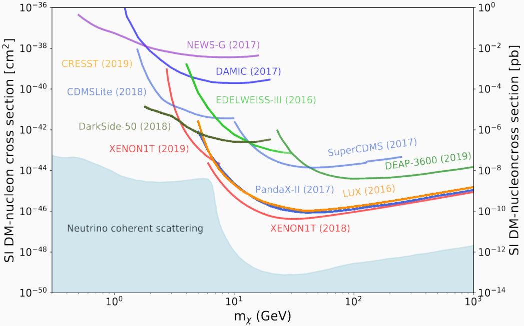
- A class of particles that interact only through the **weak nuclear force** and gravitation
- $m_\chi \sim (\mathrm{MeV} - \mathrm{TeV})$



Most of the detectors are using the DIRECT DETECTION strategy:

- The WIMP would produce an elastic collision on a target nucleus **inside** the detection volume
- Measurement of the energy of the induced nuclear recoil

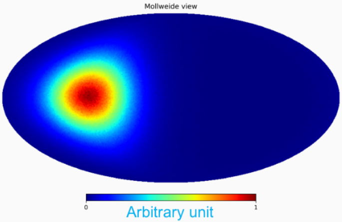
WIMP - Strategy of detection (2/2)



Particle Data Group, **2020**

WIMP induce the same signal than:

- Neutrons
  $\rightarrow$ can be partially shielded
- Neutrinos
  $\rightarrow$ cannot be shielded
  $\Longleftrightarrow$ **Irreducible background**



Galactic map of the WIMP angular distribution

Tao, Beaufort *et al.*, 2003.11812

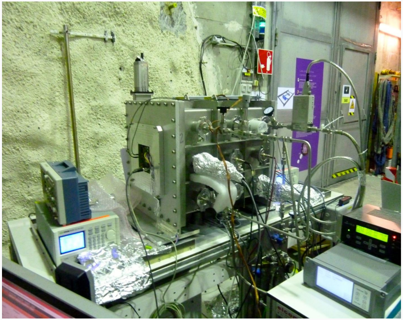
The WIMPs form a static halo surrounding the galaxies:

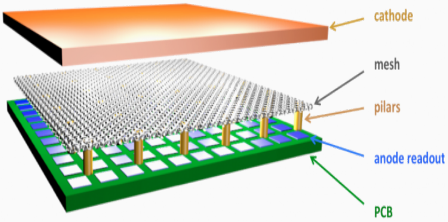
- They enter the detector with a favoured direction
- This anisotropy gives a unique signature
- **Measuring the direction** of the nuclear recoil enables to overpass the irreducible background and **is mandatory for an unambiguous detection**

$\Longleftrightarrow$ Principle of directional detection

MIMAC = MIcro-TPC MAtrix of Chambers

- Directional detector developed at LPSC
- Gaseous detector → we can easily adapt the properties (target mass, spin, pressure) to confirm possible candidates
- **Measure simultaneously the energy and the 3D track in an adaptable energy range $[150\,\text{eV}, 30\,\text{MeV}]$**
- Sampling at $50\,\text{MHz}\,(20\,\text{ns})$
- Based on a Micromegas with a pixelated anode





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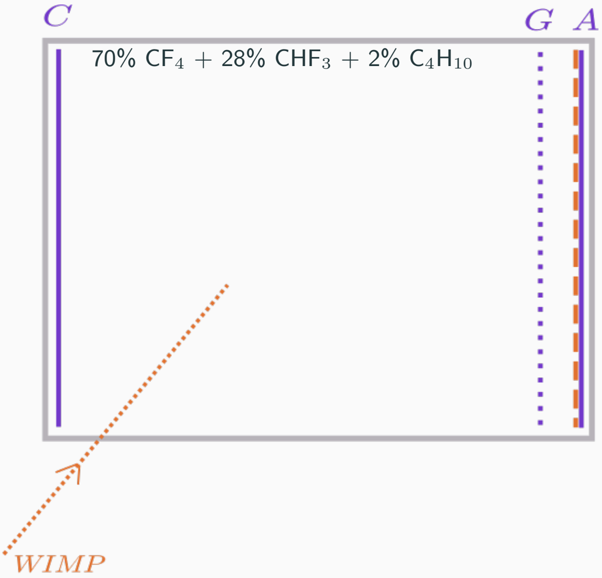
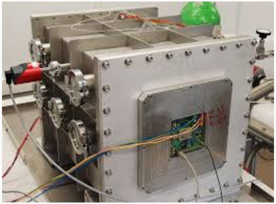
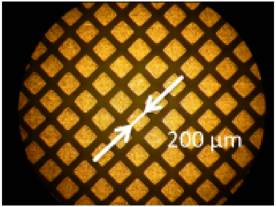
- Micromegas concept -

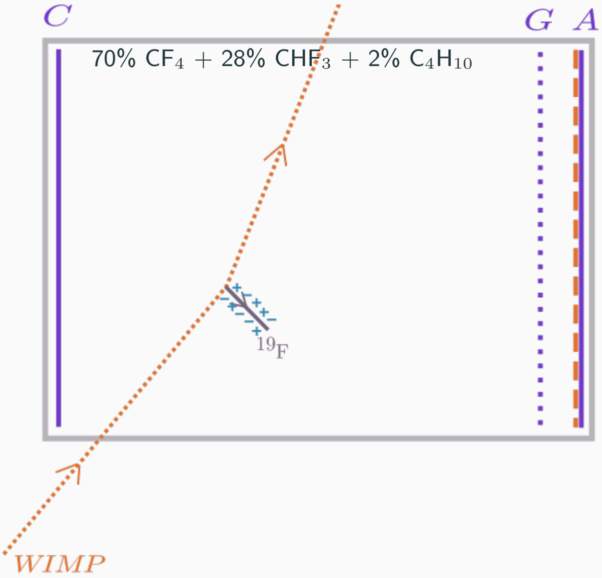


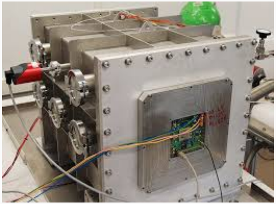


MIMAC bi-chamber



Anode





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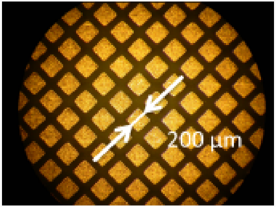

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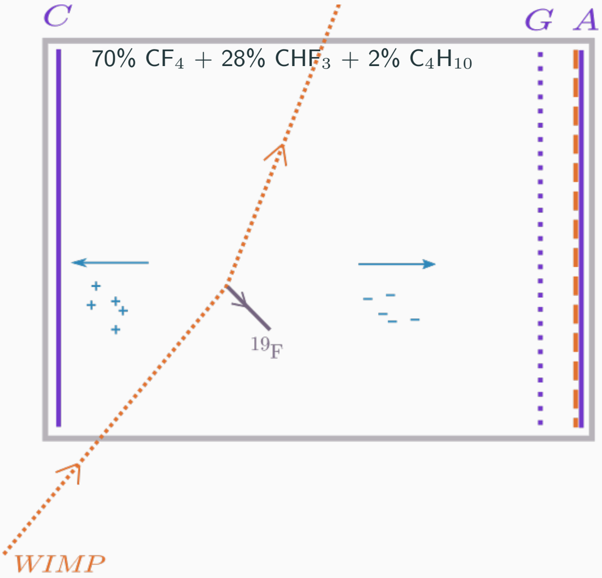

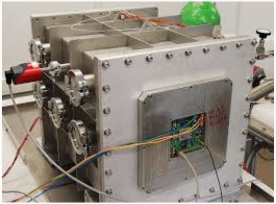

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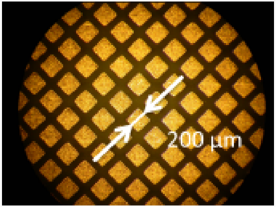

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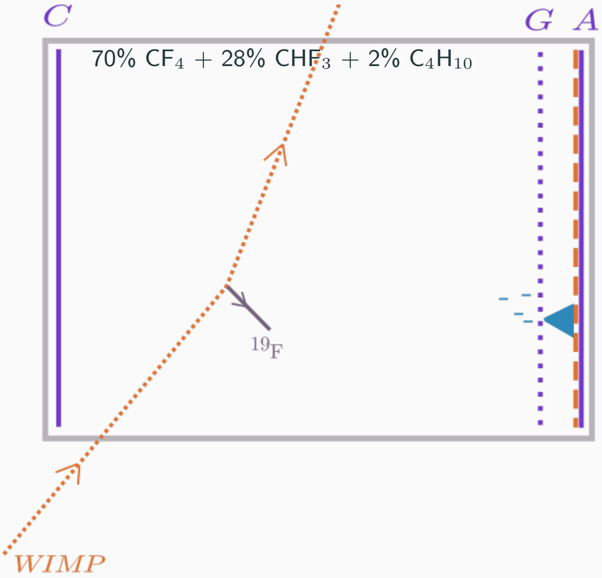
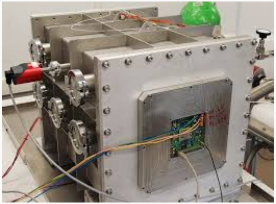
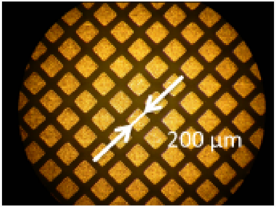


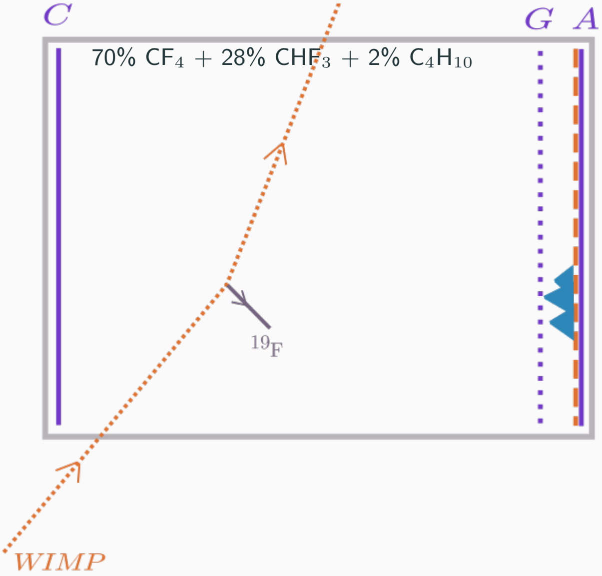


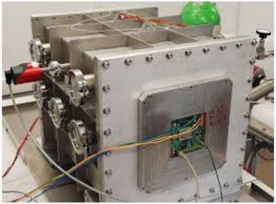
MIMAC bi-chamber



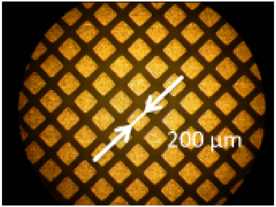
Anode

WIMP - The MIMAC detector (2/3)





MIMAC bi-chamber



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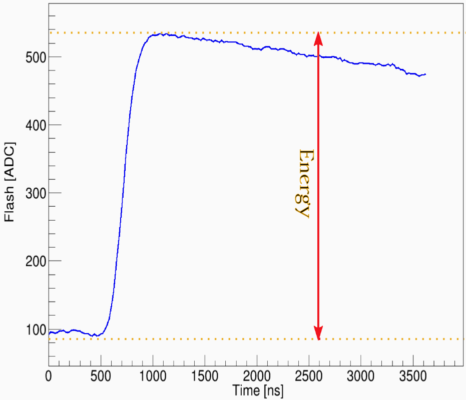
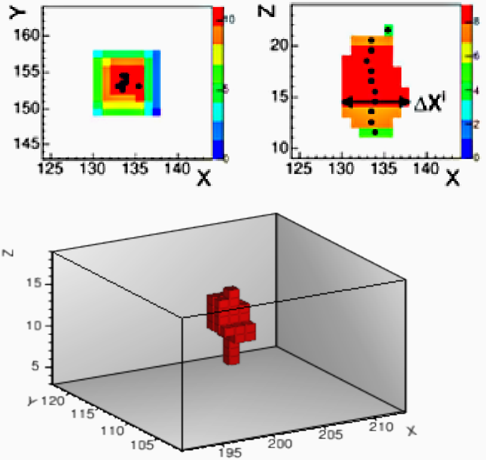


(a) *Measure of the energy (Grid)*

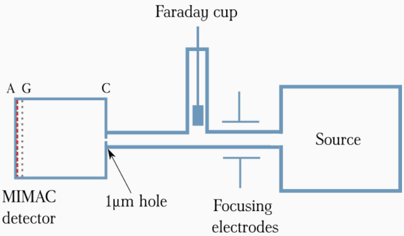


(b) *Strips and 3D reconstruction (Anode)*

⟶ Sampling every **20 ns**

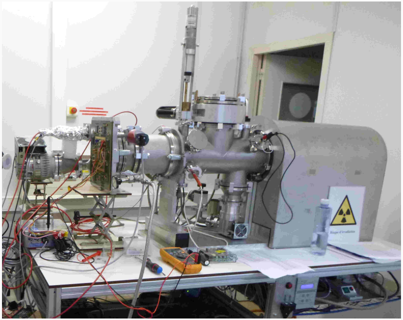
COMIMAC = source of ions and electrons of known kinetic energy

- $E_K \in [150\,\text{eV}\,,\,30\,\text{keV}]$
- Accurate tool: $\delta E_K \sim 1\%$
- Developed at LPSC



USED FOR:

- Calibration
- Physical measurements (track length, straggling, diffusion)
- Ions/electrons comparison



QUENCHING FACTOR:

- $Q = E_{ioni}/E_K = f(E_K,\ Z,\ p,\ \text{gas})$
- Crucial measurements to determine the kinetic energy of a recoil from the measured ionization energy

Directionality at high gain

Directionality at high gain - Statement (1/2)

At low gain, for $E_K > 20\,\mathrm{keV}$ we have demonstrated that MIMAC can achieve directionality with a good angular resolution.

The goal is to cover the low energy range $E_{\mathrm{Recoil}} \in [1\,\mathrm{keV}\ ,\ 20\,\mathrm{keV}]$ for which there is a lack of experimental searches.

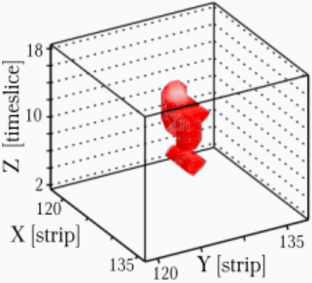
$\Rightarrow$ Low energy $\iff$ Shorter tracks $\iff$ Less directional information

$\Rightarrow$ **We must work at high gain**

We wrote 2 papers showing high-gain measurements with $E_K \in [6\,\mathrm{keV}\ ,\ 26\,\mathrm{keV}]$:

- 3D tracks reconstruction (Tao, Beaufort *et al.*, **2021**, published in NIM-A)
- Angular resolution (Tao, Beaufort *et al.*, submitted to NIM-A)

$\Longrightarrow$ My main contribution for those papers was to simulate the setup and to compare to the measurements



3D track of a $6.32\,\mathrm{keV}$ Fluorine

Directionality at high gain - Statement (2/2)

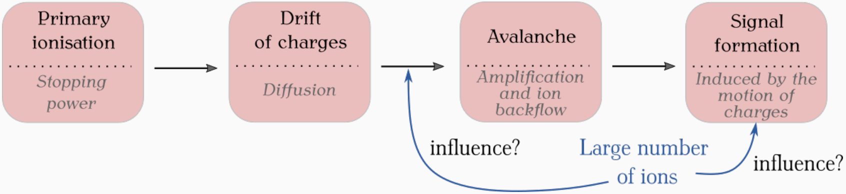
The results in our papers are pretty good and unique (3D tracks at low energy) but **we observed an elongation of the measured tracks** that required a correction

Evidence for a non-linear effect at high-gain:

- The correction applied behaves as if the drift velocity was changing all along the arrival of charges
- **We described precisely the phenomenon** by performing several experiments with Comimac
  $\Longrightarrow$ we determined an empirical correction for the papers
  $\Longrightarrow$ we still needed to understand the physics behind this non-linearity

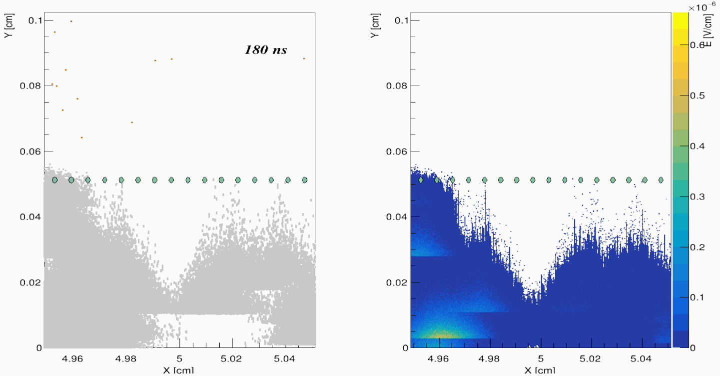
$\Longrightarrow$ What is it? How does it impact the directionality?

Directionality at high gain - Simulations (1/3)



Simulations:

- As far as we know there is no tool to simulate the motion of charges taking into account the induced EM field.
- I have implemented a library that simulates in 2D all the steps from the primary ionisation to the signal formation. The motion of electrons (drift and avalanche) is deeply inspired by the *Garfield++*'s source code
- At each timestep, the induced electromagnetic field is computed from the position of all the charges in the gap and the particles are drifted (or avalanched) accordingly.



- Video of the motion of charges -

⟹ In the simulations, the local distortions of the electromagnetic field are not strong enough to explain the measurements

⟹ The long simulation work leaded to another hypothesis

Directionality at high gain - Simulations (3/3)

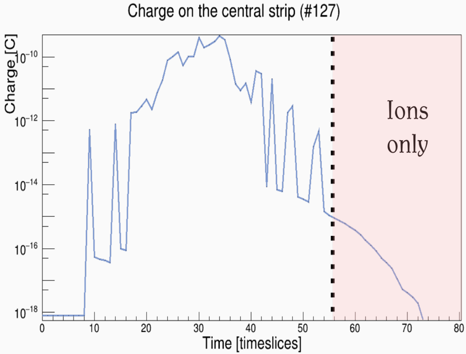
Current induced by the ions:

- Ramo theorem:

$$i(t) = \sum_{k=i,e} q_k \, \mathbf{E}_{w,k} \cdot \mathbf{v}_k$$

with $\mathbf{v}_e \sim 10^3 \, \mathbf{v}_i$

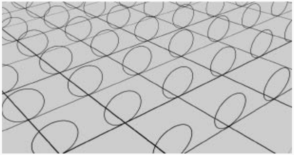
- Ions induce less current than electrons but they remain longer in the gap



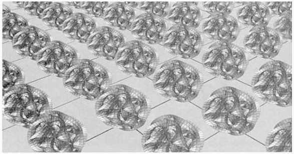
Summary of directionality at high gain:

- At high-gain it seems that we get sensitive to the current induced by the ions
- **The simulations reproduce the measured elongations of the track**
- This hypothesis must be validated on other measurements
- We will study how to improve the angular resolution within this hypothesis
- Final validation with a beam of 8 keV neutrons (they induce the same signal than WIMPs). *Experiment in May 2021 with the AMANDE facility at Cadarache.*

Kaluza-Klein axions



$n = 1$



$n = 6$

Extra spatial dimensions:

- Assume there are n extra spatial dimensions compactified with radius $R < 30\,\mu\mathrm{m}$
- Axions can propagate in $\delta < n$ extra dimensions
- Framework proposed in the 90's to solve the hierarchy problem (among other features)

Why such a framework?

- Theoretically motivated
- Why not? ;) $\longrightarrow$ extra spatial dimensions are experimentally allowed
- Opens up the window for axions searches with a MIMAC-like detector
  - Without extra dimensions, event in the case of Axion-Like Particles (ALP), our detection window is excluded by astrophysical constraints (from *Extragalactic Background Light*)

KK axions - Theoretical aspects (2/3)

Axion in extra dimensions:

- The axion is a hypothetical particle postulated to solve the Strong CP problem. It is also a good DM candidate
- From our 4-dimensional world, the $(4+\delta)$-axion is seen as an almost infinite superposition of state called a Kaluza-Klein (KK) tower

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a\, F^{\mu\nu} \tilde{F}_{\mu\nu} \xrightarrow[\text{from 4D brane}]{(4+\delta)\text{ axion seen}} \frac{g_{a\gamma\gamma}}{4} \left(\sum_{n=0}^{\infty} r_n a_n \right) F^{\mu\nu} \tilde{F}_{\mu\nu}$$

Consequences:

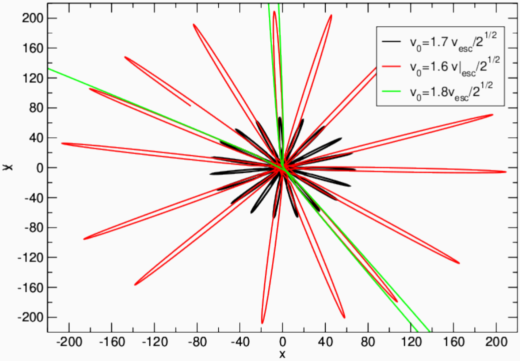
- KK axions would be produced in the Sun with $m_a^{KK} \in [1\,\mathrm{keV}\,,\, 30\,\mathrm{keV}]$
- In comparison with the standard QCD case, the KK axions are significantly more massive, more abundant, and with shorter lifetimes

$\Longrightarrow$ Opens the detection channel via the decay $a \to \gamma\gamma$

$\Longrightarrow$ KK axions can be used as a probe for extra dimensions

Trapped KK axions:

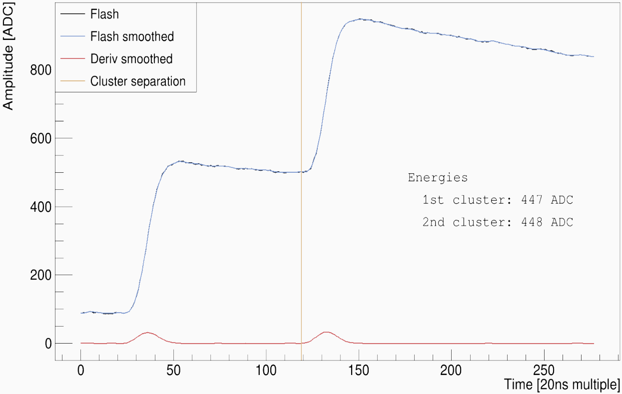
Some of the KK axions produced in the Sun are sufficiently non-relativistic to be **trapped into the solar gravitational field**. They will then start to orbit the Sun and they accumulate over the Sun history.



Orbits of trapped KK axions.
In unit of solar radius.

$a \to \gamma\gamma$ SIGNATURE:

- 2 photons of same energy emitted back-to-back $\Longrightarrow$ photoelectric effect
- Search for 2 electrons of same energy ($\sim 4\,\mathrm{keV}$) close to each other



We use Comimac at high-rate to generate a pile-up of two electrons of same energy ($4\,\mathrm{keV}$) in one time window

$\Longrightarrow$ **Unambiguous signature**, almost no background event can reproduce such signal

$\Longrightarrow$ From Monte Carlo simulations, we estimate 70% of efficiency of detection

Need for a model revision:

There is a dozen of theoretical papers about KK axions but **only one article about trapped KK axions**: DiLella & Zioutas, 2003. This paper pioneers the model however it is somehow cryptic with few equations, it contains almost no details about how the main results are derived and the results are model-dependent.

Some detectors use the D&Z model to search for KK axions: DRIFT, XMASS, News-G

Our contributions to the model:

- Derive analytically all the D&Z results to cross-check them and to obtain model-independent expressions
- Update the astrophysical constraints with recent measurements

Organisation:

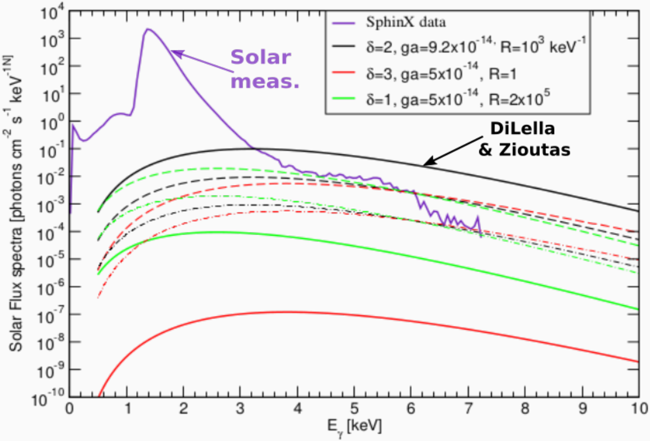
We work with **Mar Bastero-Gil**, a theoretician from the Granada University

- Mar derives the expressions
- I implement Monte Carlo simulations to cross-check the main results

KK axions - Model revision (2/3)

Main constraint: the solar flux of photons

The decay of trapped KK axions would contribute to the solar flux of photons. It should not exceed the measurements.



⟹ Preliminary results (*to be confirmed*)

⟹ The D&Z model seems ruled out

⟹ The coupling to photons $g_{a\gamma\gamma}$ must be reduced to fulfil the constraint

⟹ Reduce the event rate in a detector

KK axions - Model revision (3/3)

MAIN RESULTS ON KK AXIONS:

- We have entirely revised the model
- We reduce the D&Z event rate by 2 orders of magnitude
- The event rate would be $R \sim 1\ \mathrm{event/year/m^3}$
  $\Longrightarrow$ recent result, *to be confirmed*
- Challenging but conceivable in a large MIMAC-like detector ($50\,\mathrm{m}^3$, same volume than for WIMP searches)

Conclusion

Conclusion

Summary:

- MIMAC is a directional detector that can simultaneously search for low-mass WIMPs and Kaluza-Klein axions
- At high gain (for the low energies), the detector suffers from a non-linear phenomenon

  $\Longrightarrow$ I have implemented a simulation library that gave us a promising explanation
- With Mar Bastero-Gil we have entirely revised the solar KK axions model

  $\Longrightarrow$ the event rate reduces significantly

Outlook:

- Confirm the final result about KK axions and publish the revision of the model
- Use my simulation toolkit to explain the non-linearities at high gain

  $\Longrightarrow$ Compare with neutron data

  $\Longrightarrow$ Main goal of my thesis: to show the directional performances at high gain
- Publish measurements (Quenching factor) for the News-G collaboration

  $\Longrightarrow$ draft half written
- Show 3D electron tracks below $500\,\mathrm{eV}$ and how we can use them as counters of primary electrons (with an intern student coming this summer)

Backup

Directionality

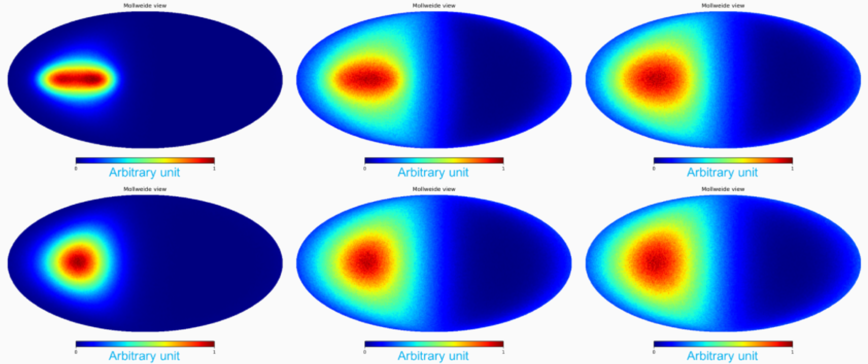
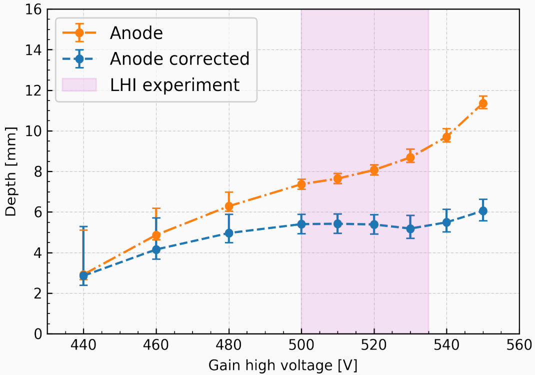


Figure 12. From left to right : WIMP angular distribution, WIMP-induced recoil angular distribution with perfect resolution and with finite resolution (15°). Top: Pure halo component model with $r = 0.0$. Bottom: Two-component model with $r = 0.5$.

Tao, Beaufort *et al.*, 2003.11812

According to J. Billard (ex PhD student in the MIMAC team), the detection of 50 WIMP events is enough to distinguish from any background signal



Comimac experiment: send $5\,\mathrm{keV}$ electrons and vary the MIMAC gain $\Longrightarrow$ The measured depth increases with the gain

- When we applied a correction (obtained from the charge measurements) we can almost recover the expected plateau and we can match the simulated data.
- The correction applied behaves as if the drift velocity was decreasing all along the arrival of charges

$\Longrightarrow$ **Evidence for a non-linear effect that depends on the gain**

$\Longrightarrow$ What is it? How does it impact the directionality? Can we correct it?

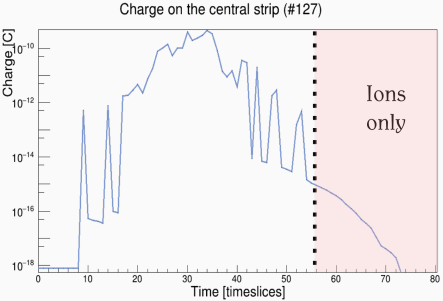
Current induced by the ions:

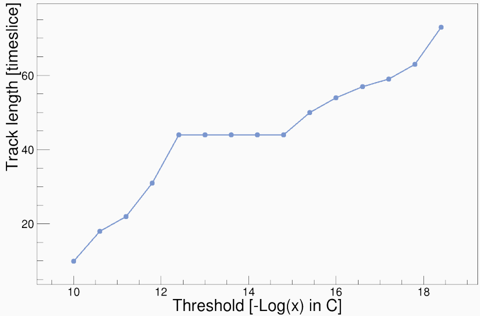
- Ramo theorem:

$$i(t) = \sum_{k=i,e} q_k \, \mathbf{E}_{w,k} \cdot \mathbf{v}_k$$

with $\mathbf{v}_e \sim 10^3 \, \mathbf{v}_i$

- Ions induce less current than electrons but they remain longer in the gap





High gain

$\Longrightarrow$ more ions in the gap

$\Longrightarrow$ larger ionic current

$\Longrightarrow$ the charge remains longer above the strip threshold

$\Longrightarrow$ measures a longer track

$\Longrightarrow$ **we can reproduce the measured non-linearities**

KK axions density:

Produce axions in the Sun
Draw variables r, m, E

↓

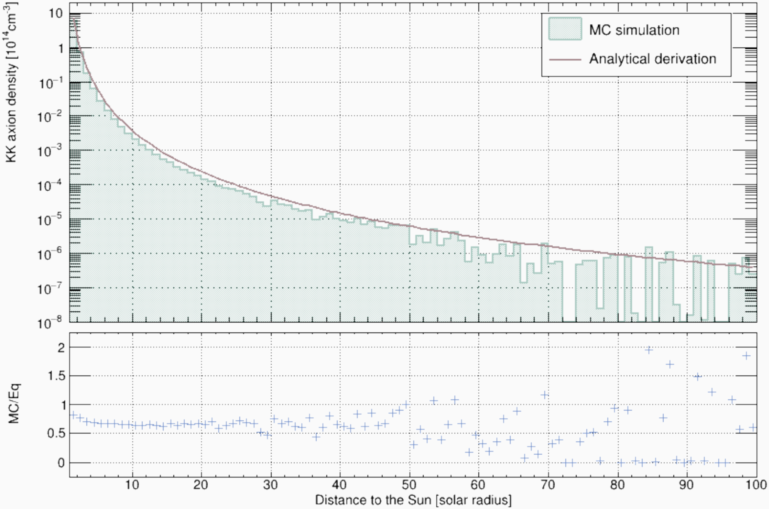
Solve Equations of Motion
Get x(t) and y(t)

↓

Increment time
Axion decay and accumulation

↓

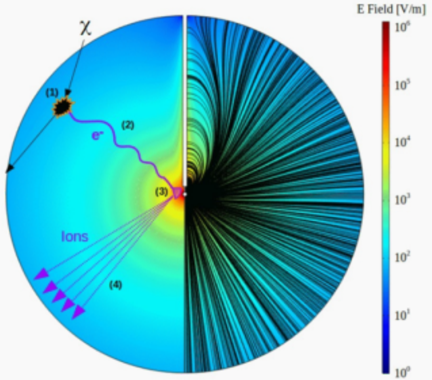
Count axions located in a box
Get n(r)



$\Longrightarrow$ We obtain a factor $\mathcal{O}(50)$ less than D&Z

News-G:

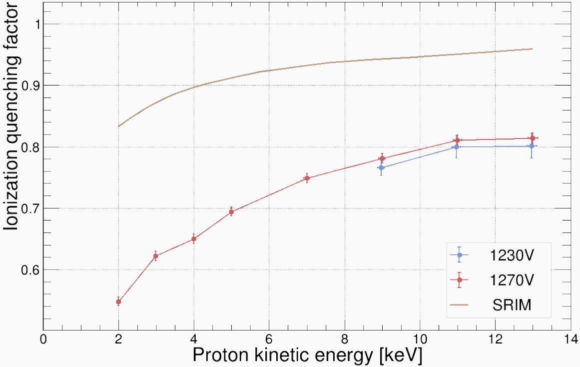
- Spherical detector (simple concept)
- Low threshold $10\,\mathrm{eV}$
- Non-directional
- Gaseous (CH_4 or Ne mixtures)
- Large mass ($1.4\,\mathrm{m}^3$ at 3 bar)
- Will take data in a few months



Complementarity between MIMAC and News-G:

- Both search for low-energetic events
- News-G will explore the low-mass WIMP region which is still unknown. If it detects something, a directional detector (as MIMAC) would be required to confirm the detection
- We compare some measurements in the 2 detectors

Ionization Quenching Factor:



- $Q = E_{ioni}/E_K$
- $Q = f(E_K,\ Z,\ p,\ \text{gas})$
- Crucial measurements to determine the kinetic energy of a recoil from the measured ionization energy
- We use Comimac to measure the Quenching factor

- As usual, we measure a Quenching factor lower than the SRIM simulation
- Our measurements are still discussed in the News-G collaboration
- We have shown some non-linearities in the News-G detector probably due to a space-charge effect

$\Longrightarrow$ Comparing the behaviours of News-G and MIMAC shines light on some issues