2023 Enigmass plenary meeting

Directional detection of dark photons at the LPSC

M. Bastero-Gil, **Cyprien Beaufort**, A. Catalano, D-S. Erfani-Harami,
O. Guillaudin, D. Santos, S. Savorgnano, and F. Vezzu

- 20th of October 2023 -

Paper on arXiv next week

A brief history of the project

- **Spring 2022**: Discussions about DP directional detection
- **15 September 2022**: Deadline for Enigmass R&D proposals

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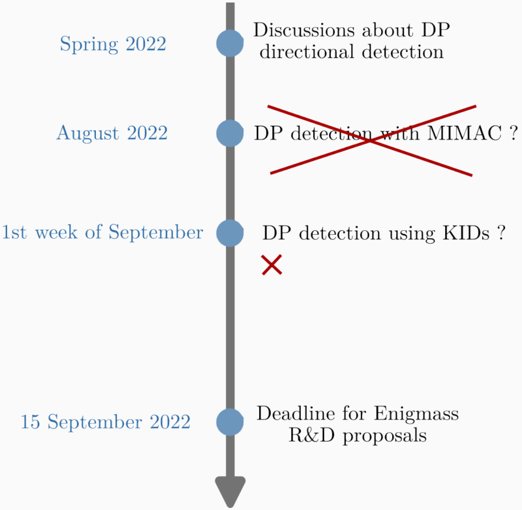

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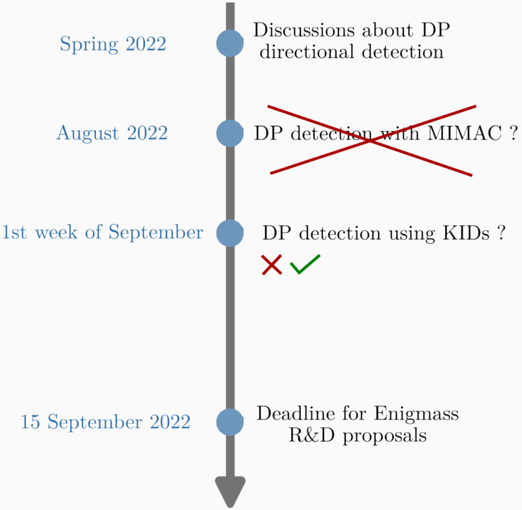

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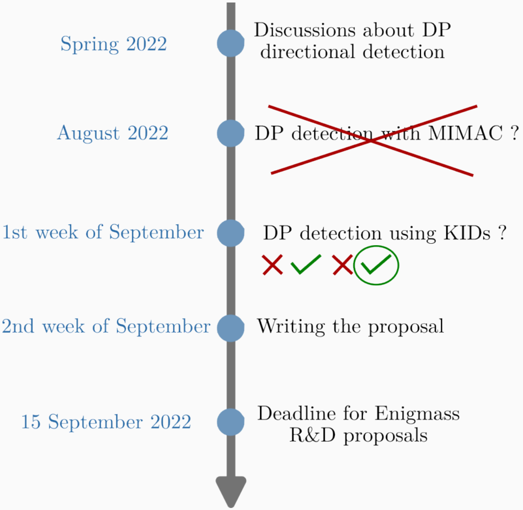
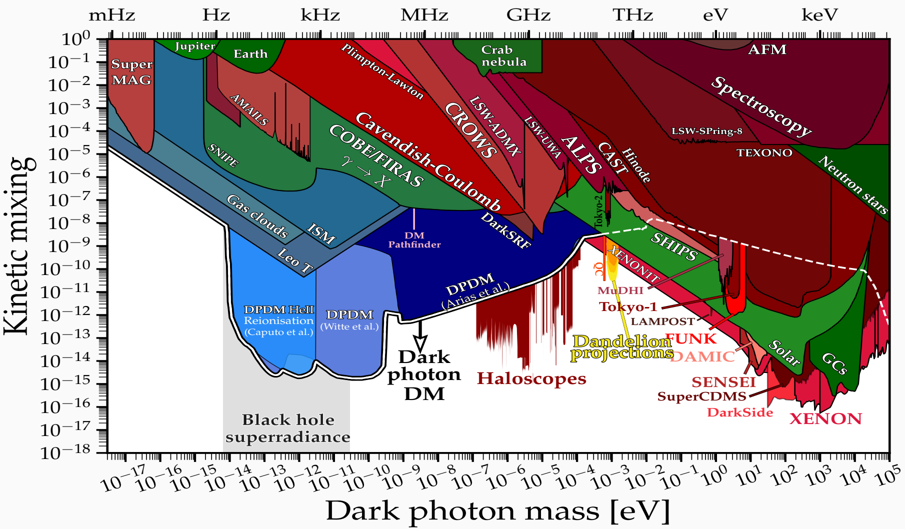


Spoiler of this presentation



Outline

1- Dark photons near the meV

Dark photon

New $U'(1)$ symmetry:

Let's suppose the existence of a new $U'(1)$ symmetry

$$\mathcal{L}_{U'(1)} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu$$

- SM fields are uncharged under $U'(1)$
- The dark photon (DP) is a spin-1 boson associated with $U'(1)$
- **The DP can be an appropriate cold dark matter candidate**

Kinetic mixing:

Because the SM also contains a $U(1)$ symmetry, there is **necessarily** a mixing between the two gauge bosons

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\chi}{2}F_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu + eJ_\mu^{em}A^\mu$$

The standard photon and the DP can go into each other as they propagate

Dark photon polarization

Since the DP is a spin-1 boson, it has a polarization

Polarization at production:

For a DP with a mass near the meV, the inflationary production of longitudinal and transverse DPs are mutually excluded

$\implies$ **The measurement of the DP polarization can probe the Early Universe**

Polarization today:

- The *fixed* scenario $\iff$ the polarization has survived until today
- The *random* scenario $\iff$ the polarization has evolved and can take any value

2- Directional detection

Definition

DIRECT DETECTION:

Measurement of an interaction between a dark matter particle and a SM particle happening inside a detector

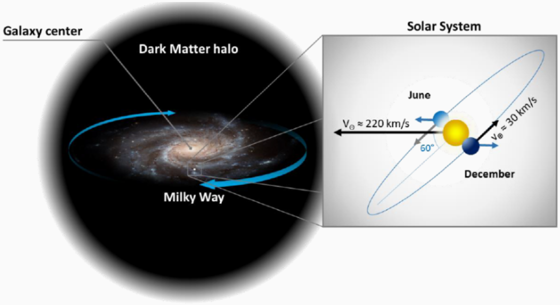
$\Longrightarrow$ The background can be reduced but never entirely suppressed

DIRECTIONAL DETECTION:

A direct detection having an unambiguous signature that can be discriminated from the background

$\Longrightarrow$ Mandatory for dark matter discovery

The galactic DM halo



Credit: A. Zani

A static halo of dark matter particles would surround the galaxies

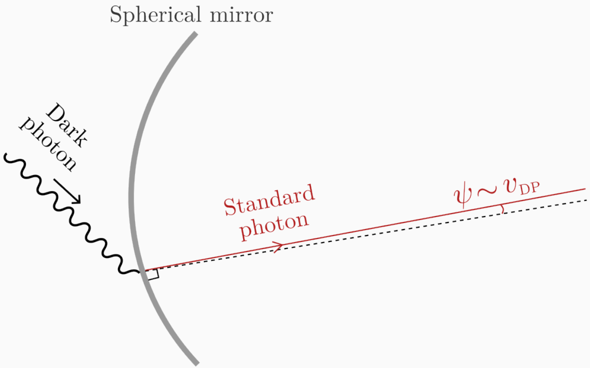
A detector on Earth has a relative motion wrt. to the halo due to:

- the rotation of the Earth
- the revolution of the Earth around the Sun
- the motion of the Sun in the galaxy
- the galactic rotation at the position of the Sun

$\Longrightarrow$ The velocity vector of a DM particle entering a detector is known!

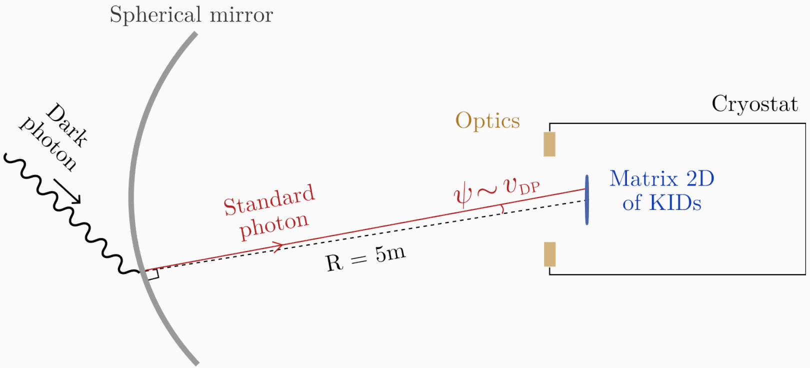
$\Longrightarrow$ **A correlation between the measured signal and this velocity can provide a directional signature**

3- The Dandelion experiment



1. The oscillating electric field of a DP induces an electric field on a metallic spherical mirror
2. By conservation of the longitudinal electric field, an ordinary photon is emitted with $E_\gamma = m_{DP}$
3. The emission has an angle $\psi \simeq v_{||}^{DP}$ from the normal of the mirror

Working principles (Horns et al., 2012)



4. The photon converges to the detector, a matrix of KIDs cooled down to 150 mK by a cryostat
5. The detector has 418 pixels to measure the angle $\psi \implies$ **directional signature**
6. The mirror is tilted at 1 Hz to move the signal spot and thus measure the background

Dande-what?

DANDELION = DArk photoN DirEctionaL detectION

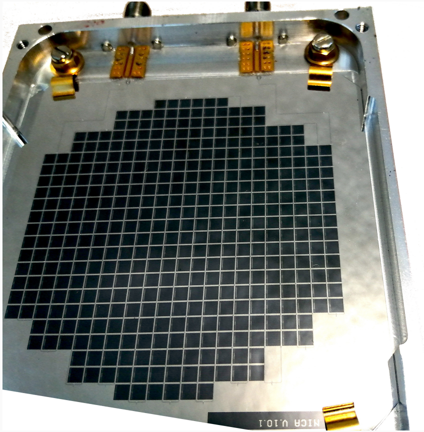
A Dandelion in the wind - Creative Commons

Just as the pappus on a dandelion flies away according to the direction of the wind, Dandelion could trace its measurements back to the direction of the DP wind due to the motion of the Earth through the DM halo.

The Dandelion experiment

Dandelion **benefits from the local expertise** and the detectors developed for astrophysical purposes:

- the KIDs
- the cryostat
- the electronics

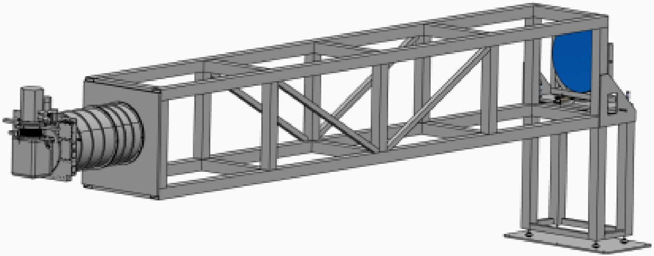


The matrix of KIDs

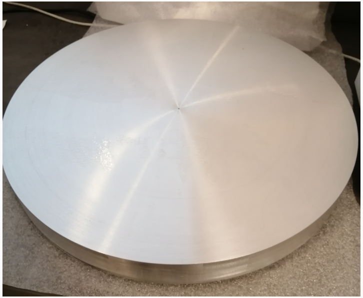
Characteristics of the Dandelion prototype:

- Mirror diameter = 50 cm
- Curvature radius of the spherical mirror R = 5 m
- Matrix of 418 KIDs of size 2.8 x 2.8 mm^2
- Bandpass in [180, 360 GHz] with a maximum at 250 GHz (1 meV)
- Mirror tilting by 5 mrad at 1 Hz

The important role of the LPSC mechanical support

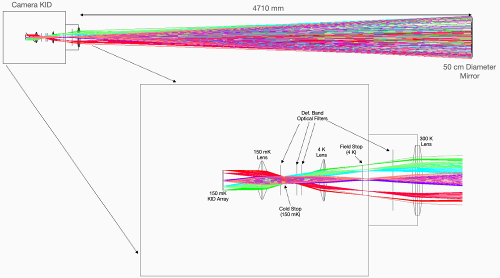


CAD of the setup made by F. Vezzu



Picture of the mirror

The mechanical structure and the mirror have been built at the LPSC



Zemax simulation of the setup by A. Catalano

THERMAL BACKGROUND:

The background is minimized by the optics placed in front of the KIDs such as the input pupil is smaller than the mirror

$\Longrightarrow$ **The thermal background is at 150 mK**

$\Longrightarrow$ The mean NEP (Noise Equivalent Power) is equal to 3×10^{-17} W/$\sqrt{\text{Hz}}$

The background is continuously measured thanks to the mirror tilting

4- Signal modelling

DP-induced power

DP-induced power on the KIDs:

$$P(x, y, t; E_\gamma) = \chi^2 \, \rho_{\rm CDM} \, \eta(E_\gamma) \, A_{\rm mirr.} \, I\big(x, y, t\big) \, \cos^2 \alpha(t)$$

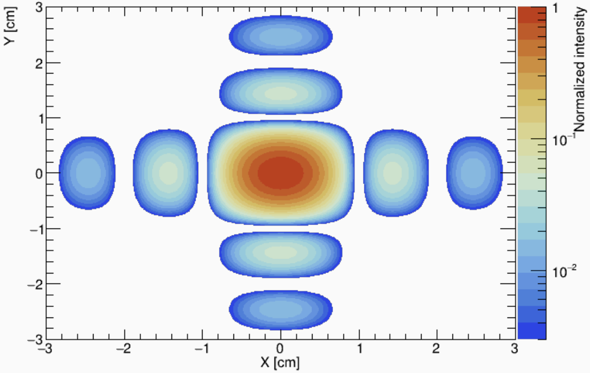
- $\rho_{\rm CDM} = 0.45 \ {\rm GeV} \cdot {\rm cm}^{-3}$ is the local DM density
- $\eta(E_\gamma)$ is the KIDs detection efficiency
- $A_{\rm mirr.}$ is the surface of the mirror
- $I\big(x, y, t\big)$ is the normalized signal spread at t
- $\alpha(t)$ is the angle between the DP polarization and the tangent of the mirror

Signal modulations:

- Spatial modulation of $I\big(x, y, t\big)$
- Intensity modulation of $\alpha(t)$

Fresnel diffraction:

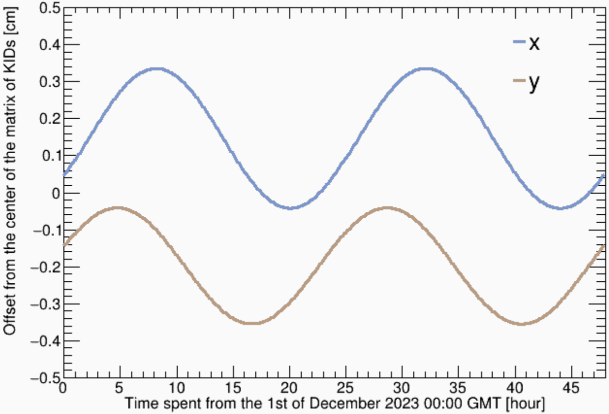
$$E(x,y,R) \simeq \frac{e^{-ikR}}{i\lambda R}\int_{\text{mirr.}} dx'dy'E(x',y',0)\,\exp\left(-\frac{ik}{2R}\left((x-x')^2+(y-y')^2\right)\right)\exp\left(\frac{ik(x'^2+y'^2)}{2R}\right)$$



2/3 of the signal is contained in the 13 central pixels

Spatial modulation: the directional signature

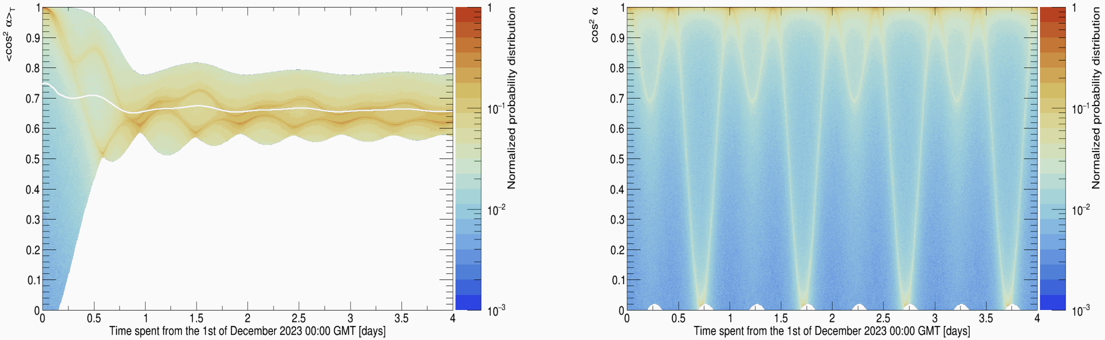
The DP-induced photons are emitted with an angle $\psi = v_{||}^{DP}$ from the normal to the surface of the mirror.
This angle depends on the motion of the mirror with respect to the DP galactic halo.



The spatial modulation is large enough to measure a directional signature

Intensity modulation

The power is proportional to $\cos^2 \alpha(t)$ with $\alpha(t)$ the angle between the mirror's tangent and the DP polarization



Time-average $\langle \cos^2 \alpha(t) \rangle$ (left) and instantaneous $\cos^2 \alpha(t)$ (right) for randomized polarizations

The intensity modulation can differentiate between the *random* and the *fixed* polarization scenarios

5- Expected sensitivities

Timeline

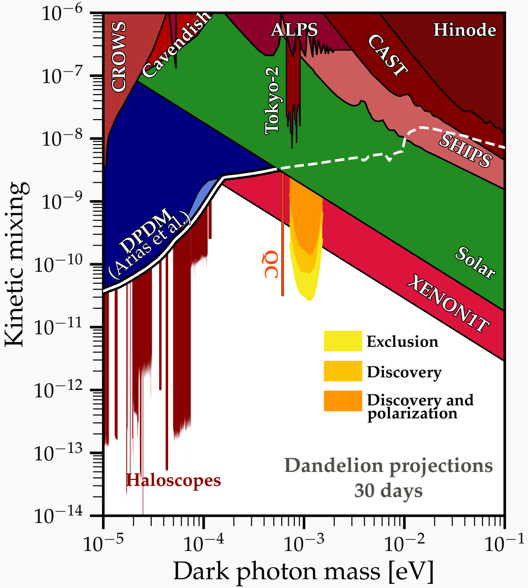
Project status:

- **The manufacturing of the pieces is done**
- The last elements will be received by the end of October
- The paper describing the projected will be placed on arXiv by the end of October

Next steps:

- November: experiment installation
- **December: 24h test run**
- Beginning of 2024: physical run

Projections



Exclusion:

A 30-day measurement would improve by **more than one order of magnitude** the existing limits

Discovery:

The directional detection leads to an **unprecedented discovery potential**

Discovery and polarization:

The detection of a DP could allow the **identification of its polarization**

Conclusion

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Take home messages:

- The DP is a good DM candidate predicted by multiple extensions of the SM
- Directional detection is mandatory to discover a DM particle
- Dandelion benefits from the expertise and equipments of the LPSC. The first data acquisition is planned for December
- The expected signal has two modulations: a spatial modulation (= the directional signature), and an intensity modulation (enabling polarization determination)
- The first Dandelion prototype can improve by more than one order of magnitude the existing limits in only a 30-day campaign

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Thank you for your attention