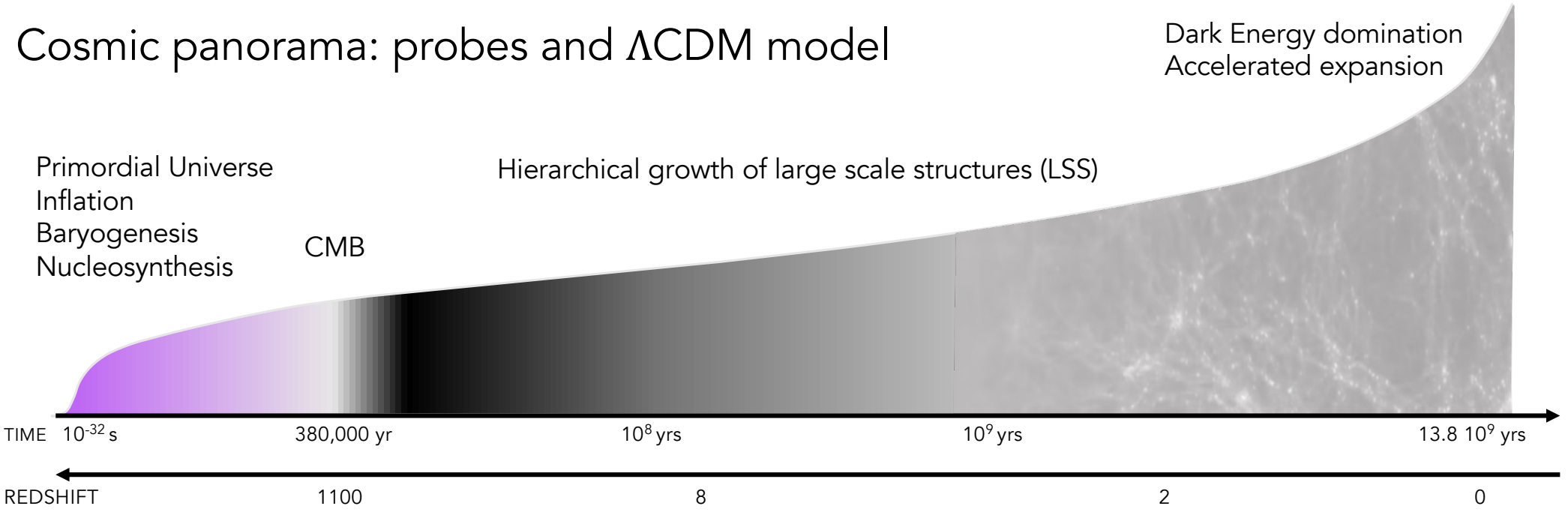
WP3 - From the primordial Universe to the Dark sector

Francesca Calore & Laurence Perotto

Contributors: David Andriot, Mateo Fernandez-Torreiro, Thibault Guillemin, Marine Kuna, Killian Martineau, Azadeh Moradinezhad Dizgah, Jérémie Quevillon, Daniel Santos, Silvia Scorza, Christopher Smith

Cosmic panorama: probes and ΛCDM model

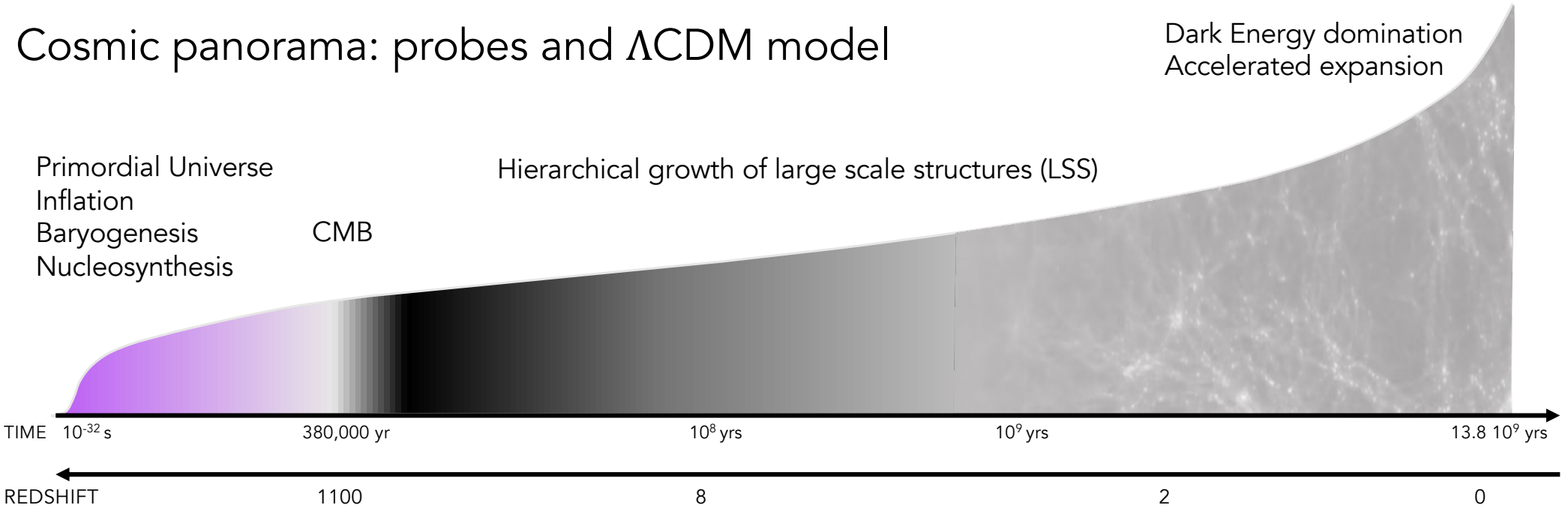


Cosmological probes

CMB primary anisotropies in temperature & polarisation
Primordial non-gaussianities

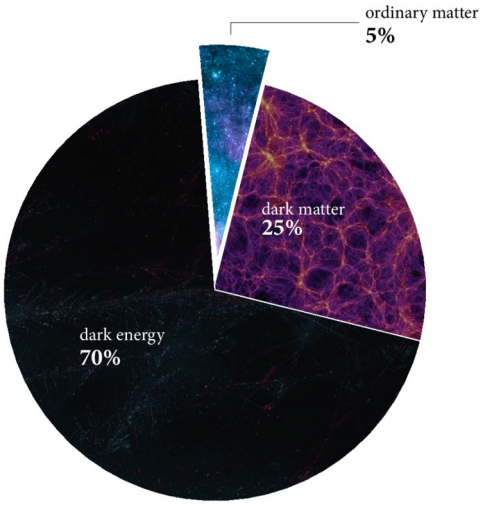
LSS probes : cosmic shear, BAO, CMB anisotropies
Galaxy clusters
Standard candles: Supernovae, gravitational waves, …

Cosmic panorama: probes and ΛCDM model



Standard model of Cosmology: ΛCDM model

- Only 6 parameters for the initial conditions, energy content, reionization history and expansion rate
- Suffice to describe all cosmological observations
- BUT 95% of the energy content is of unknown nature:
  - About 70% Dark Energy
  - About 25% Dark Matter



WP3 - Overarching questions and two-side strategy

What is the physics at play in the primordial Universe ?

→ quantum gravity
→ Inflationary phase
→ Thermal history

What is the nature of the Dark Energy ?

→ Theory & phenomenology

→ Observational Cosmology

What is the nature of the Dark Matter ?

→ Particle Cosmology

→ Observational Cosmology

→ Theory & phenomenology

→ Indirect detection

→ Direct detection

Cosmology programme

Dark Matter programme

Elements for the WP3 Cosmology programme

(Non-exhaustive lists of)

Open Questions & Cosmological probes

Early Universe

Which inflationary scenario?
(slow-roll, preheating/reheating)

Other ultra-relativistic particles than 3 ν families?
(N_eff, Primordial Black Holes)

Are there tensions between early and late universe?
(H0, S8)

Can Dark Matter interpreted in modifying GR?

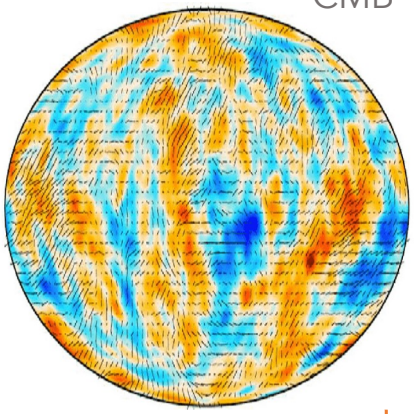
What is the absolute scale of the neutrino masses?

Is Dark Energy a cosmological constant of a fluid?
(w0, wa)

Late Universe

CMB

- Detection of primordial B mode of CMB polarization
- Primordial non-gaussianities using higher-order statistics



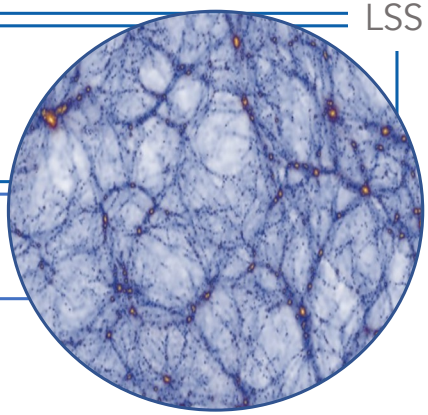
- Small angular scales of CMB T & P anisotropies

- Mapping the Dark Matter
  - Cosmic shear
  - Galaxy clustering
  - CMB lensing

} 6 x 2 point correlation functions

LSS

- Abundance of galaxy clusters
  - Galaxy richness
  - Thermal Sunyaev-Zeldovich effect



- Lots of others : Line Intensity Mapping, SNIa, kinetic SZ, Ly-alpha, GW ….

Millimeter-domain: WP3 contributions to the landscape of experiments

High-resolution experiments with SZ science case

CONCERTO

- Interferometer at 12-m APEX telescope, Chile
- Build in Grenoble
- Decommissioned in 2021

NIKA2 [Talk by Alice Moyer-Anin]

- KID-based camera at 30-m IRAM telescope, Spain
- Build in Grenoble
- Open to community in 2017 – up to 2027
- 2 Cosmology-oriented Large Programmes 300+300 h of Guaranteed Time
  - NIKA2 Cosmology Legacy Survey – P.I. LAM + IPAG
  - SZ mapping of clusters of galaxies **– P.I LPSC**

CMB experiments

Simons Observatory

- SO nominal: 4 Small (0.5 m) + Large (6 m) Aperture Telescopes in Chile
- Frequency coverage: 27 – 280 GHz
- First light in 2024
- CMB B-modes ($\sigma(r) = 0.002$) + SZ effects & CMB lensing

KAIROS

- Project of a French SAT, equipped with 30,000 KIDs, covering 200-400 GHz
- Mitigation of the dust contamination

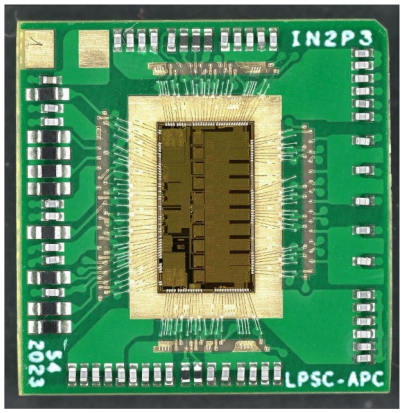
CMB-S4

- Successor of SO
- 9+ SAT & 3+ LAT in Chile (South Pole site plan discarded)
- Goal: $\sigma(r) \leq 5\text{x}10\text{-}4$

LiteBIRD

- Satellite JAXA primary miror 0.4m
- Launch around 2029, 3-yrs duration
- CMB B-modes sigma(r) ~ 0.001

WP3 Highlight on contributions to CMB-S4

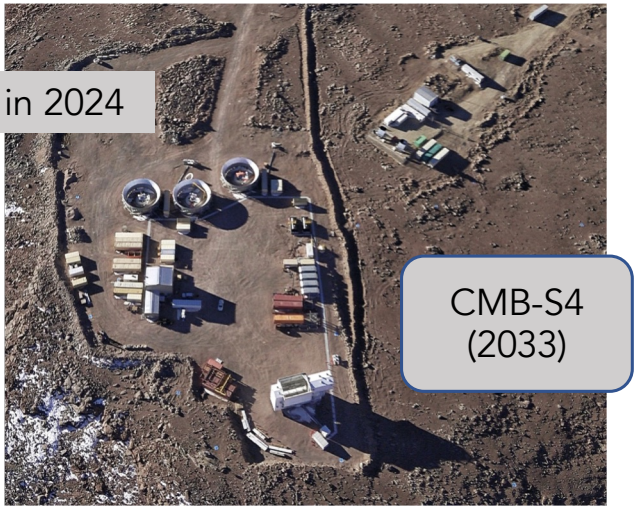


Hardware contribution

Warm electronic
LPSC in charge of creating a new packaging for the ASIC developed by the APC team

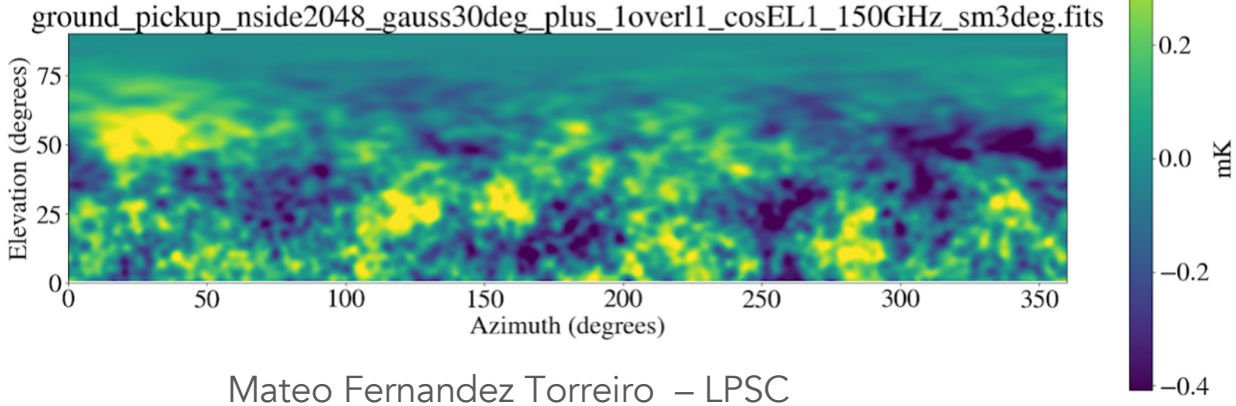
Photo from Fatah Rarbi – LPSC

Atacama desert site in Chile



Data Management

- Validation of Data Challenge 0 (DC0) sims = 10% of the total data set
- Production of the ground-pickup noise component simulations for the first set of Chile-only simulations.



Mateo Fernandez Torreiro – LPSC

Science Working groups

- Galaxy clusters, contribution to the Science Book

Optical / Near IR surveys: WP3 involvements

Vera C. Rubin Observatory

8-m telescope in Chile (Cerro Pachón)
3.10^9 CCD camera
covering 6 optical bands
Currently being installed
Legacy Survey for Space & Time (LSST)
Starts in 2025

Camera arrival on site in May 2024

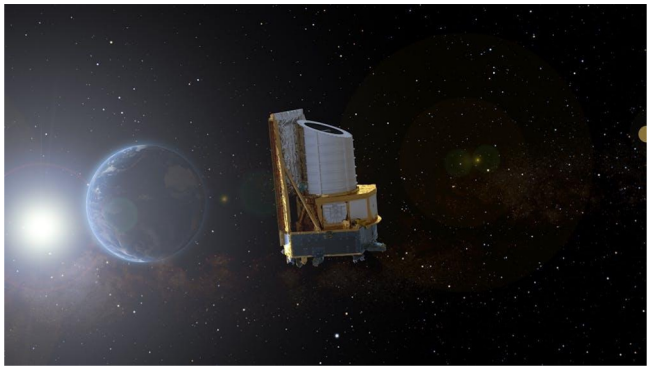
Dark Energy Science Collaboration (Enigmass contributions)

- Galaxy clusters
- Weak lensing & galaxy clustering
- Dark matter search
- Transients (WP2)

Strong contributions to the project

- Hardware: Filter loader, Optical bench
- Computing/software developments for the Data Release Processing of Rubin
- Commissioning of the Rubin camera focal plane & the mirror system of the telescope

Euclid



- ESA Class M satellite, 1.2m primary mirror
- Launched in July 2023, 6 yrs duration
- VIS: optical imager
- NISP : Near IR spectro-imager
- Main cosmological probes
  - Weak lensing
  - Galaxy clustering
  - Galaxy clusters

Phenomenology for spectroscopic surveys (e.g. DESI) → Statistical methods for accurate and unbiased inference

Highlights on WP3 contributions to Euclid

Science Ground Segment

LPSC is responsible for the production of sky masks

- Encapsulating informations of all spatial variations of global properties (survey, astrophysical foregrounds, products)
- Impact of the associated systematics on the cosmological probes (WL, galaxy clustering & galaxy clusters)

Strong contribution from the LPSC IT support service

Juan Macías-Pérez – LPSC

Galaxy Clustering Science Working Group

LAPTh cosmology is involved in higher-order statistics work package

- Developing analysis pipeline for cosmological inference from combination of 2- and 3-point clustering statistics
- Primary focus on constraining primordial non-Gaussianity & Fourier space spectra
- Investigating ML-based approaches to remove impact of line interlopers (important systematic of spectroscopic galaxy clustering)

Azadeh Moradinezhad – LAPTh

Euclid observation of the Perseus cluster

- Early Quick release in March 2025
- DR1 in June 2026

WP3 contributions to theoretical cosmology

Dark energy

- Dark energy in string theory models and associated constraints
- Quintessence phenomenology and departure from ΛCDM
- Inference on modified gravity/dynamic dark energy w/ ground-based mm-wavelength line intensity mapping

LAPTh

Quantum gravity & GW theory

- Phenomenology of the Loop Quantum Gravity
- High-frequency gravitational waves
- Stochastic gravitational wave background

LPSC GRENOBLE | MODANE

Particle Cosmology

- Primordial Black holes formation from inflaton fluctuations
- Effects of heavy sterile neutrinos in cosmology
- Dark matter production in the presence of inflaton decay

LAPTh

WP3 - Overarching questions and two-side strategy

What is the physics at play in the primordial Universe ?

What is the nature of the Dark Energy ?

What is the nature of the Dark Matter ?

→ Theory & phenomenology

→ Indirect detection

→ Direct detection

Cosmology programme

Dark Matter programme

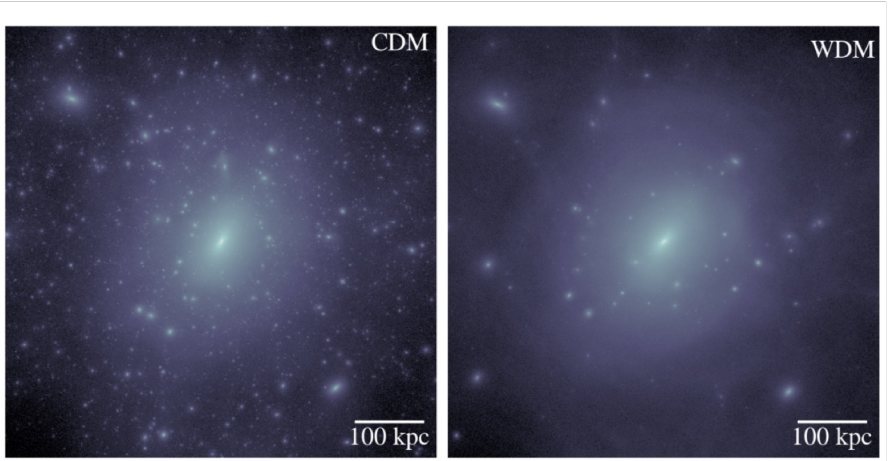
The dark matter problem: open questions

Mounting evidence from kpc-sized galaxies up to cosmological scales suggests that the majority of **pressure-less matter** in the universe is **not baryonic in nature**

While the dark matter gravitational impact is well measured, its **nature remains a mystery**

Non-exhaustive list of **open questions** in the dark matter quest:

- Is there cosmic evidence to go beyond the cold and *collisionless paradigm*?
- How is dark matter *produced* in the early universe, and how does this connect to late universe observables?
- Is dark matter a particle and fundamentally *wave-like or particle-like*?
- Is there a *dark sector* containing other new particles and/or forces? Does dark matter have important *self-interactions*?

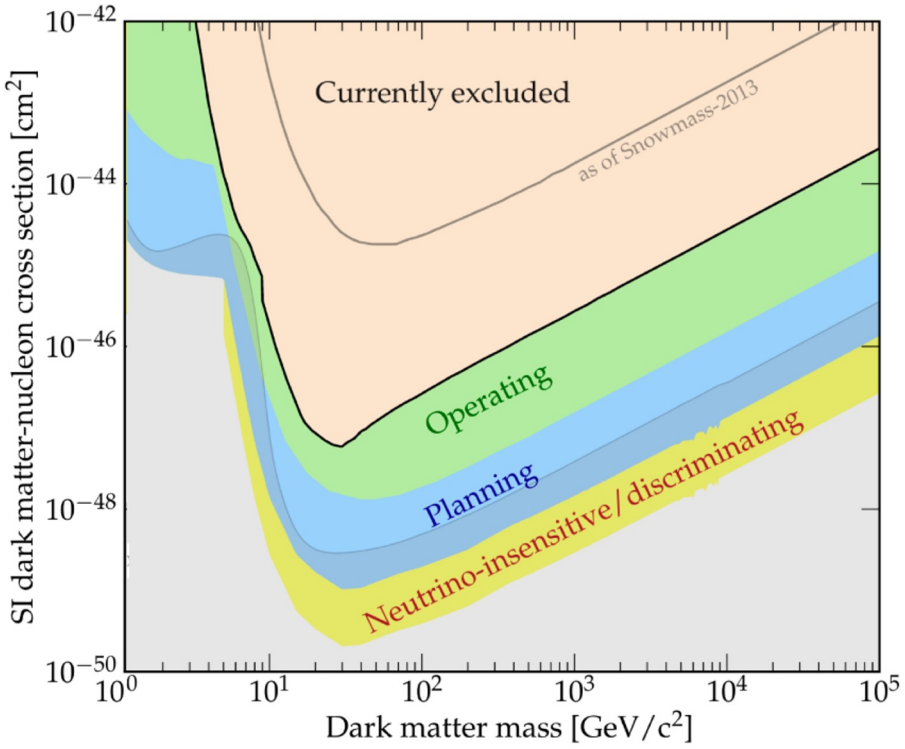


Gravitational probes for dark matter: matter power spectrum, mass spectrum, distribution, density profiles of dark matter halos, and abundance of compact objects, etc.

High-priority dark matter candidates

Weakly Interacting Massive Particles

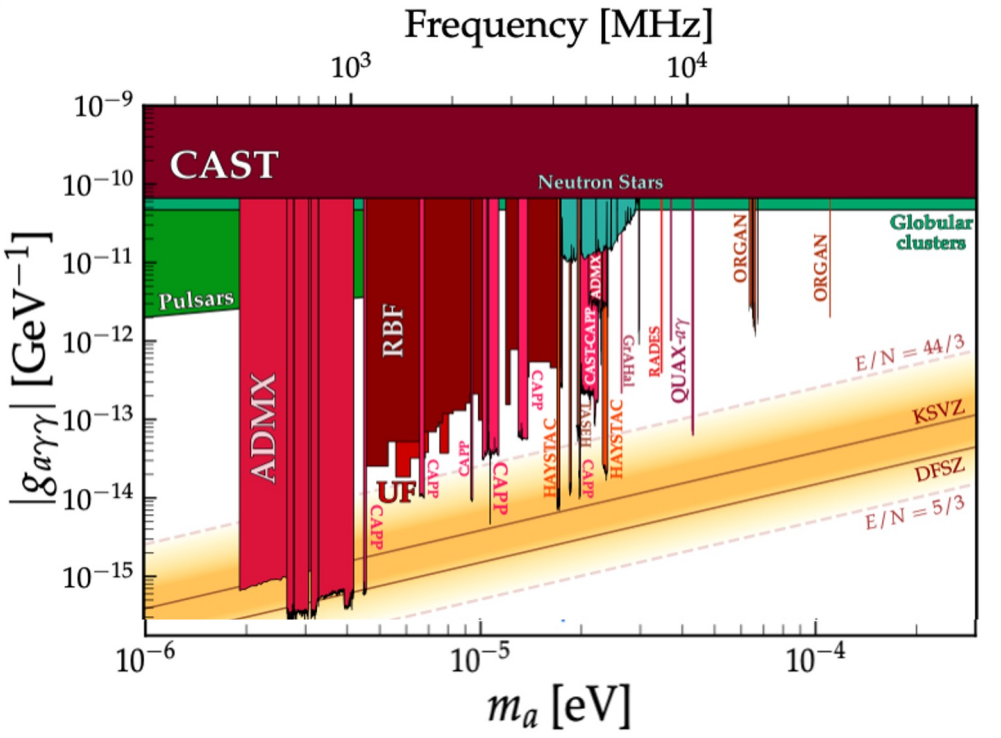
Quick ID: 1 GeV — 100 TeV, electroweak coupling with SM



Delve deep with terrestrial and astroparticle experiments

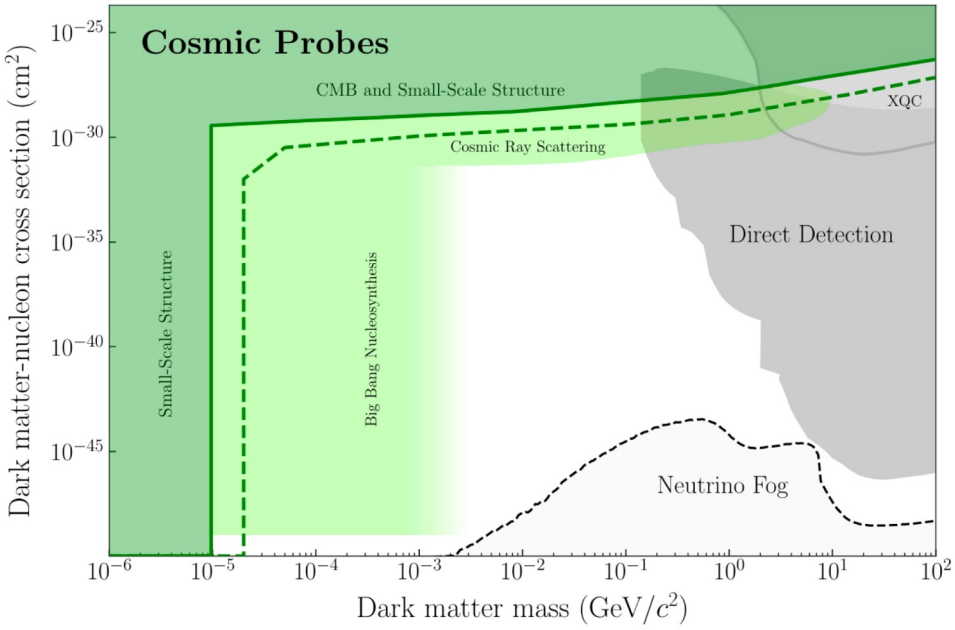
QCD Axion

Quick ID: 10^{-12} — 0.01 eV, minimal coupling with photons

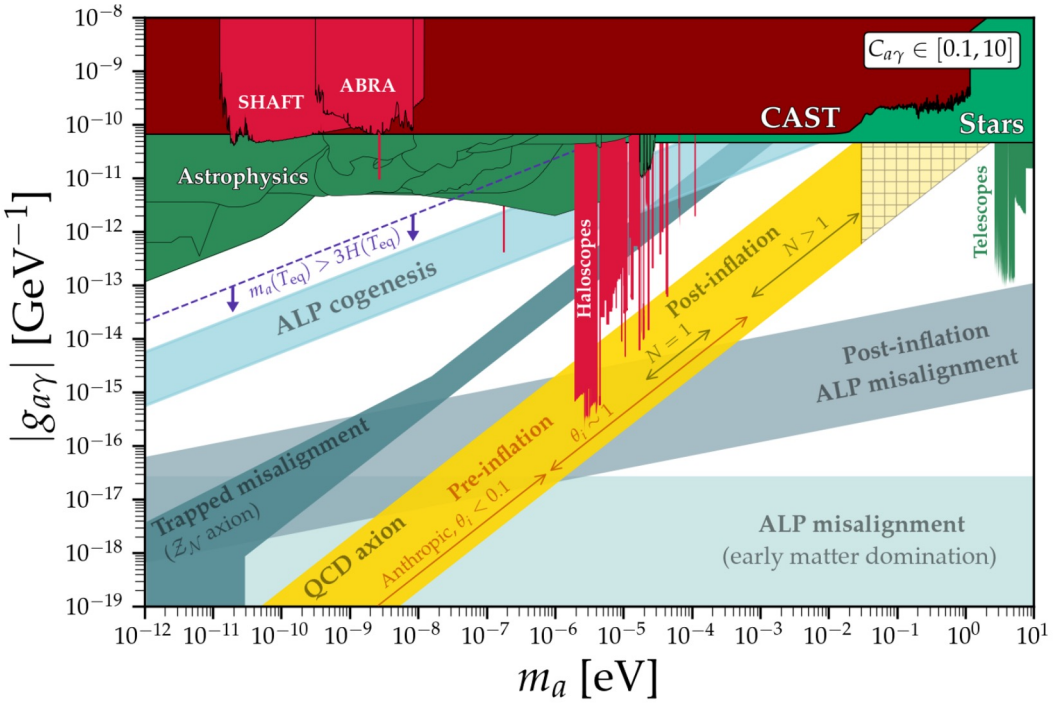


Axion CDM: $f_a \approx 10^{10}\,\mathrm{GeV}\left(\frac{0.6\mathrm{meV}}{m_a}\right)$

Broadening the dark matter landscape



Dark sectors and light DM models
Direct detection efforts to go to lower (sub-GeV) masses
Astrophysical and cosmo probes can reach the lowest masses



Axion-like particles (ALPs) models (string theory)
Astrophysical and direct probes

Non-particle DM candidates at test: Primordial black holes (PBH)
→ link to particle cosmology and inflation

WP3 contributions to the dark matter quest

Direct detection

- WIMP directional detection with MIMAC → new detector mounted and working at LPSC; @LSM in 03/25
- NEWS-G (sub-GeV) → search w/ methane target
- TESSERACT (sub-GeV)
- meV dark photon directional detection (DANDELION) → Data analysis on-going

Indirect detection

- WIMP indirect detection with cosmic rays (p-bar) and gamma rays (GeV - TeV, Fermi & CTAO)
- Light DM and PBH searches in X rays and soft gamma rays
- ALPs gamma-ray bursts from SNe
- DM searches with stellar streams (Rubin/LSST)

Theory & Phenomenology

- QCD axion phenomenology in dense media
- QCD axion couplings
- Role of baryon number in axion physics (DM axions and baryogenesis)
- Light DM candidates phenomenology and complementary constraints

WP3 Highlight on dark matter direct detection with TESSERACT

[Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets]

Silvia Scorza – LPSC

Extending the Dark Matter (DM) mass search window from meV-to-GeV with **ultra low-threshold cryogenic detectors** with **multiple targets** and **particle identification and Low-Energy Excess (LEE) rejection capabilities** with two identical cryogenic setups installed in the **ultra-low background environment underground at the Modane Underground Laboratory (LSM)**

TES4DM project approved in 2024 (RI2)

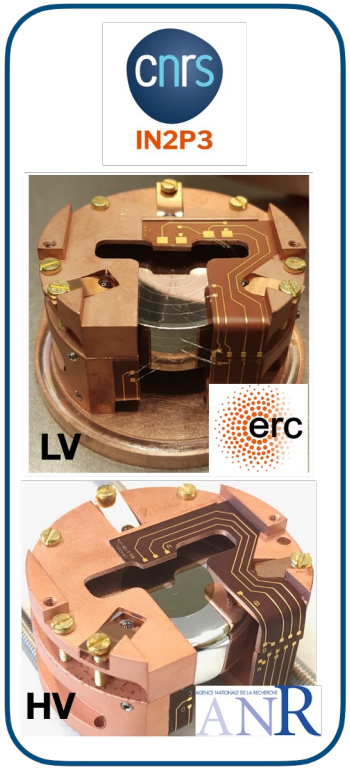
Building the next generation semiconducting low-threshold detectors operated in a ultra-low background underground cryogenic facility

Technology specifications:

- Use of Ge/Si crystals to be operated in Low-Voltage (NR) and High-Voltage (ER) modes
- Transition from NTD phonon sensors (20eV) to TES athermal phonon sensors (100 meV)
  - Understanding and mitigating the LEE seen in all solid-state direct dark matter search experiments —> Design driver

TES4DM UG facility @ LSM specifications:

- Designed to operate various technologies for a broad DM search spectrum: Ge/Si, LHe, and polar crystals
- Designed to achieve few DRU background levels
- Designed to be the new LSM DM cryogenic experiment



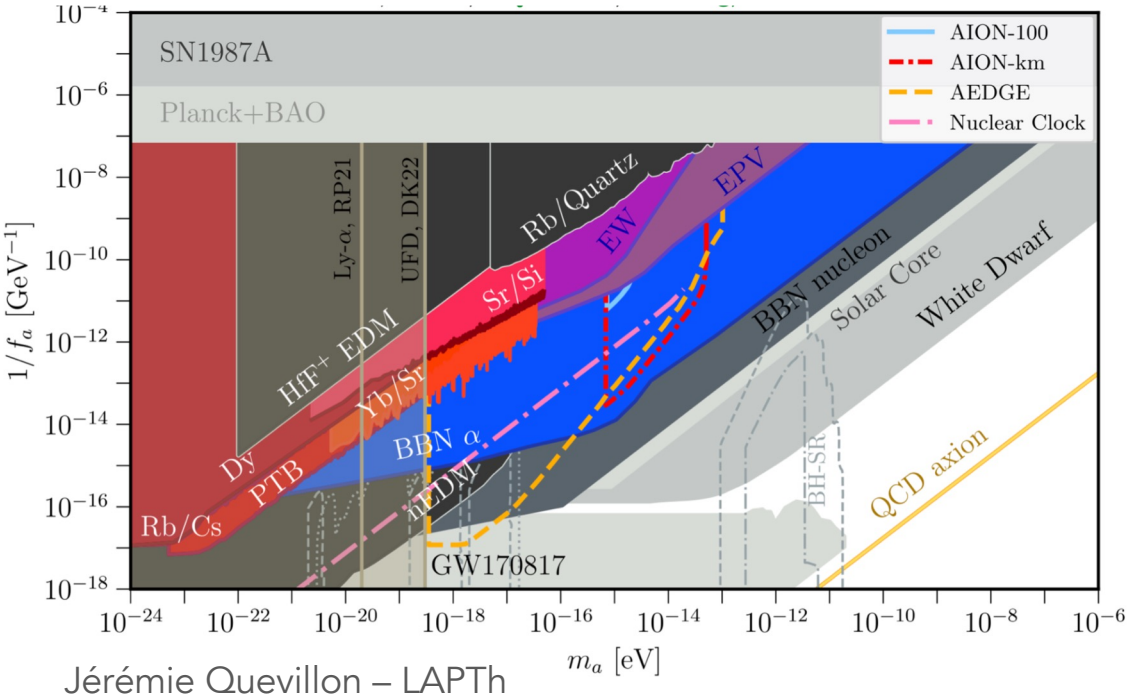
Activities at the *Laboratoire de Physique Subatomique et Cosmologie* in Grenoble:

- Shielding design and GEANT4 simulations for radioactive background characterization
- Analysis of cryogenic detectors (Low-Voltage mode via RICOCHET - CENNS search)
- TES4DM cryostat commissioning at the LPSC above-ground cleanroom (end of 2025)
- Leading underground integration at the Modane Underground Laboratory

WP3 Highlight on light dark matter candidates' indirect probes

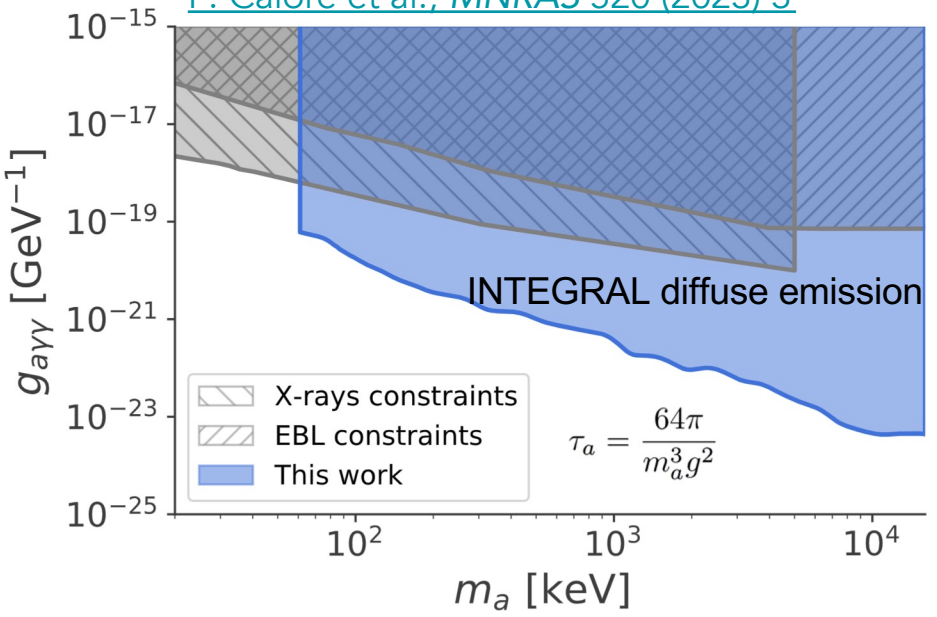
QCD axion: unavoidable 1-loop coupling w/ the electromagnetic kinetic term (aaFF) → Temporal variation of the fine structure constant **α**

Beadle et al., *PRD* 110 (2024) 3, 035019



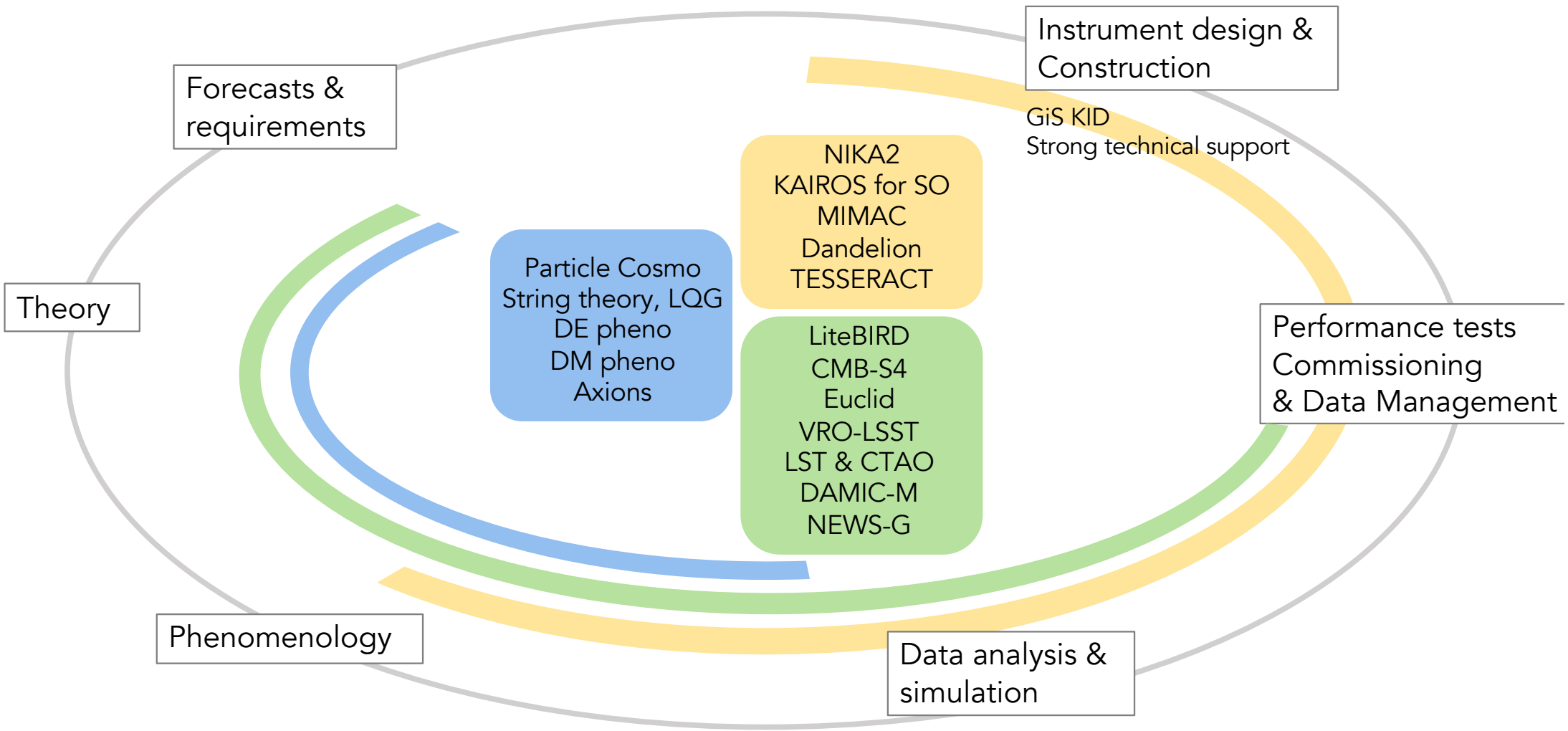
Exploration of new signatures of **axion-like particles** in gamma-ray data (supernova gamma-ray bursts, INTEGRAL/SPI diffuse emission)

F. Calore et al., *MNRAS* 520 (2023) 3



$$\frac{d\Phi_\gamma}{dE}(\ell, b) = \left(\frac{d\Phi_\gamma}{dE}\right)_{\text{diffuse}} + \left(\frac{d\Phi_\gamma}{dE}\right)_{\text{PS}} + \left(\frac{d\Phi_\gamma}{dE}\right)_{\text{DM signal}}$$

ENIGMASS+WP3 – involvement from theory to experiments



Back-up slides

WP3 highlights on NIKA2

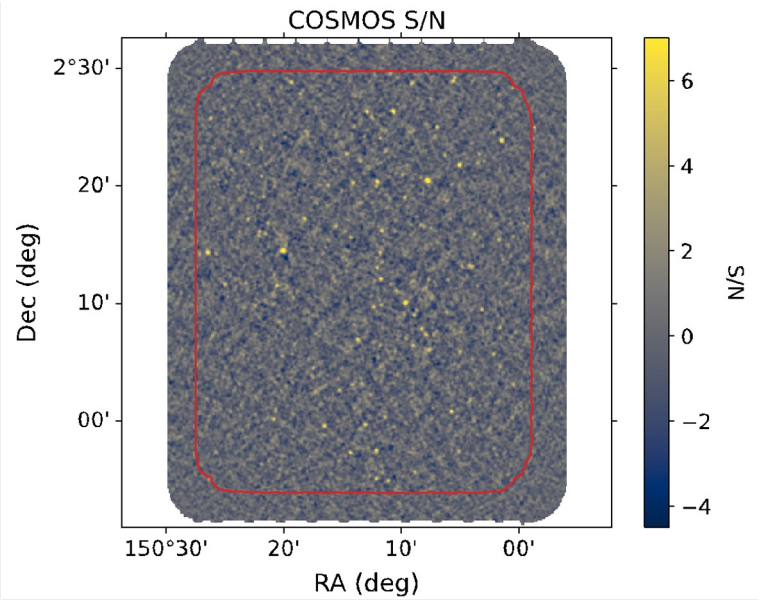
NIKA2 collaboration:

- 163 scientists from 33 Institutes in 9 countries (France, Spain, Italy, Ireland, Belgium, Greece, UK, Iran & USA)
- Responsability of the construction, commissioning, maintenance & upgrades until ~2030
- 1300 hours of Guaranteed Time at the IRAM 30-m telescope distributed in 5 *Large Programmes*, including 2 for Cosmology

NIKA2 Cosmology Legacy Survey (N2CLS)

→ Deep mm observations in Cosmos & Goods-N fields

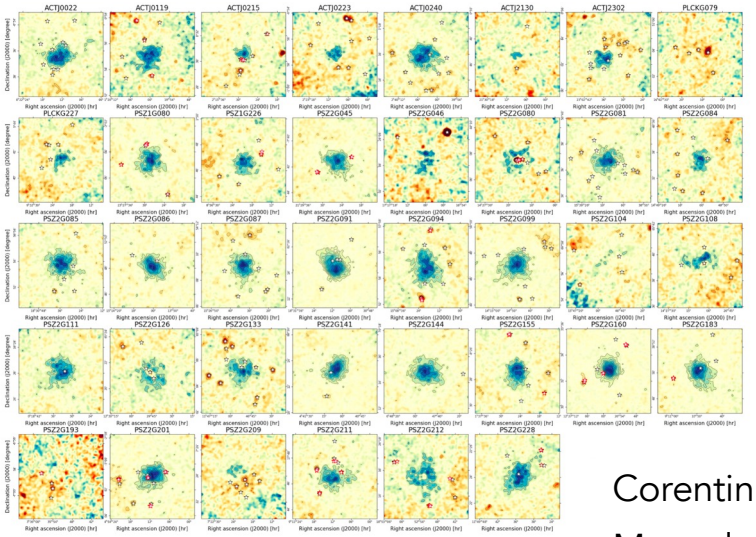
→ Studying star formation



NIKA2 SZ Large Programme (LPSZ)

→ Resolved SZ observation of 38 galaxy clusters

→ Improving tools for cluster cosmology



Corentin Hanser – PhD thesis

More details in Alice's talk

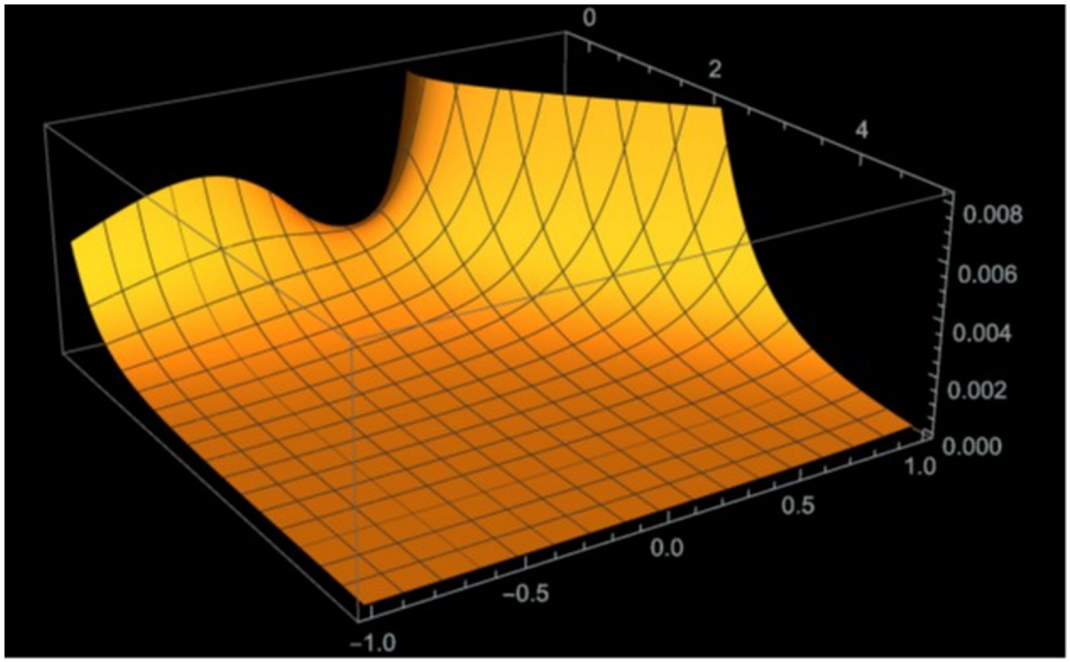
- Millimeter Universe Conference series : 3rd edition in Grenoble (2023), 4th edition in Chicago (2025)

DR1 in 2025

Example of theoretical contribution to Dark Energy (I/II)

David Andriot – LAPTh

Exploration of the possible realisations of dark energy (cosmological constant or quintessence) in string theory models, and the associated constraints (such as the strong de Sitter swampland conjecture).



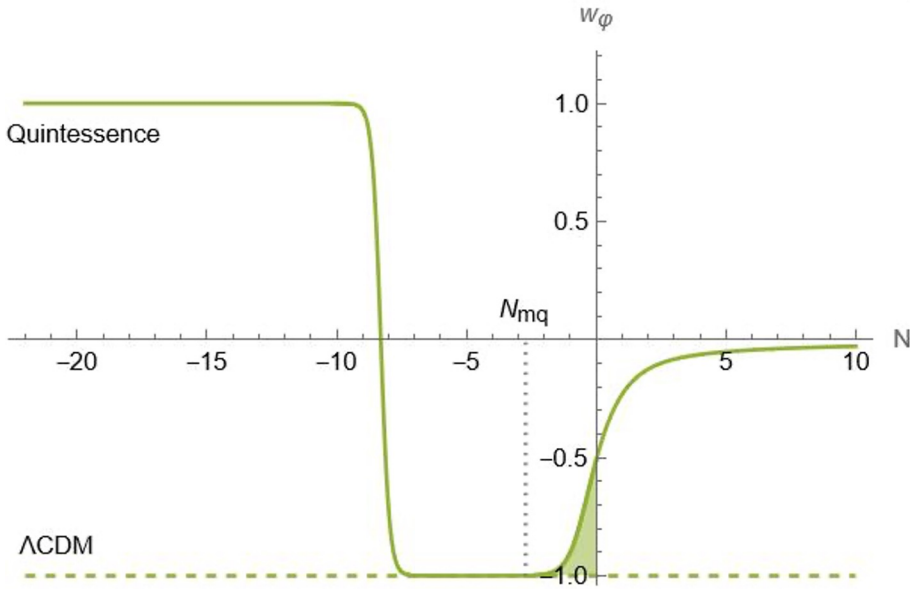
"de Sitter extremum": tentative de Sitter solution from string theory, from which one could get a cosmological constant or a quintessence scenario (extremum of a scalar potential).

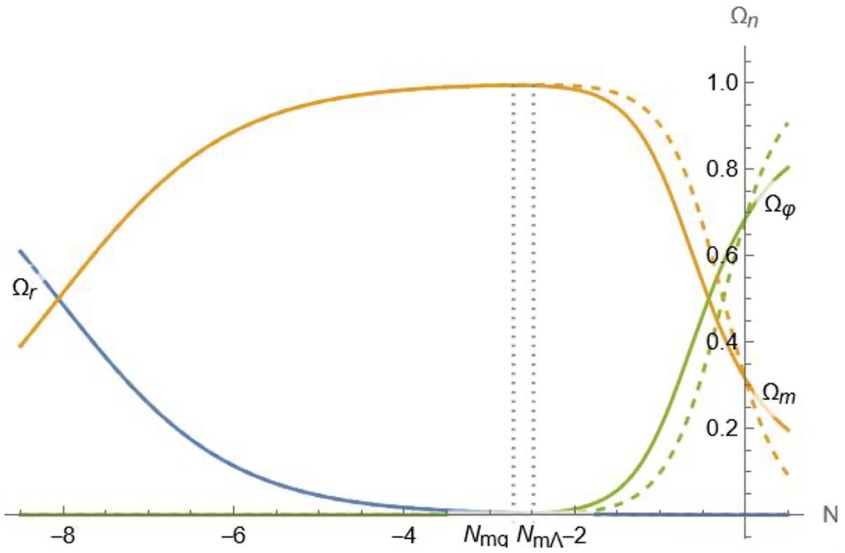
Example of theoretical contribution to Dark Energy (II/II)

David Andriot – LAPTh

Study of theoretical quintessence models that could reproduce dark energy, trying to distinguish them observationally from **Λ**CDM, and relating them to DESI results.

Plot: "figwarea" and "figOend", next to each other: this illustrates differences in the dark energy equation of state parameter, as well as in the energy density parameters Omega_n, between quintessence and **Λ**CDM. The differences illustrated by these two plots are related by an established formula in my work: int (w**φ** + 1) dN = 4/3 (Nm**Λ** − Nmq).



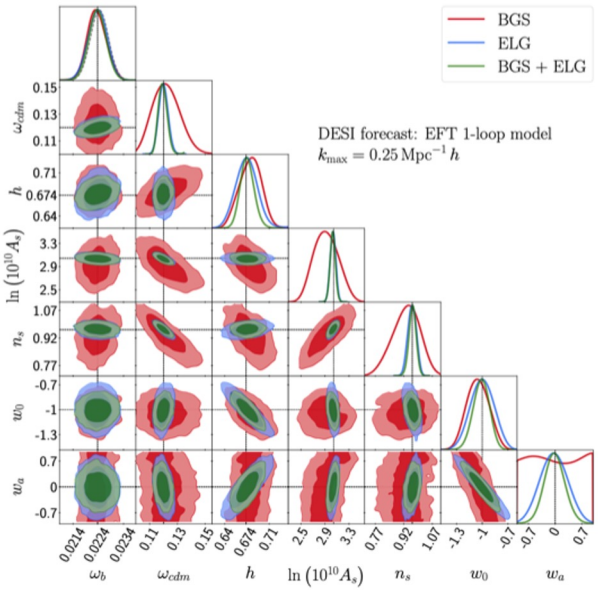


Highlights on phenomenological cosmology

Azadeh Moradinezhad Dizgah – LAPTh

- **CLASS-OneLoop: Accurate and Unbiased Inference from Spectroscopic Galaxy Surveys**

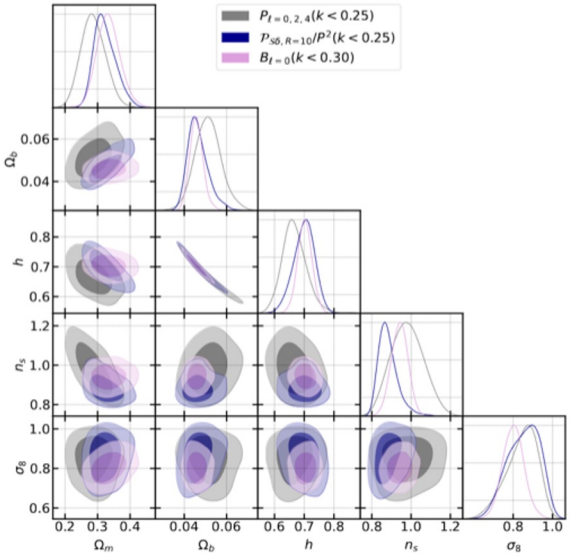
Development of highly efficient code for high-precision computation of galaxy power spectrum in redshift-space for upcoming spectroscopic galaxy surveys



arXiv: 2402.09778 (accepted in JCAP)

- **SimBIG: Cosmological Constraints from the Redshift-Space Galaxy Skew Spectra**

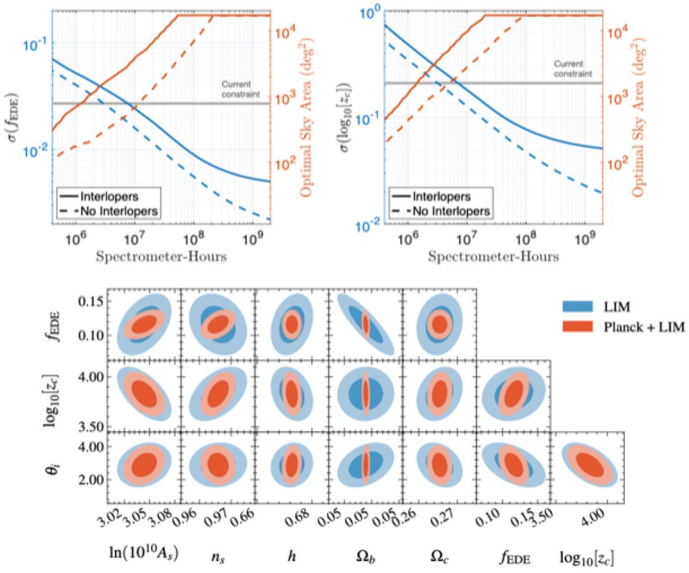
First cosmological constraints from skew spectra of BOSS galaxies using simulation-based inference



arXiv: 2401.15074 (accepted in PRD)
selected as PRD Editors' Suggestion

- **Probing Dark Energy and Modifications of Gravity with Ground-based millimeter-wavelength Line Intensity Mapping**

Extensive exploration of several classes of modified gravity/dynamic dark energy to quantify the constraining power of LIM from future ground-based mm-wavelength surveys

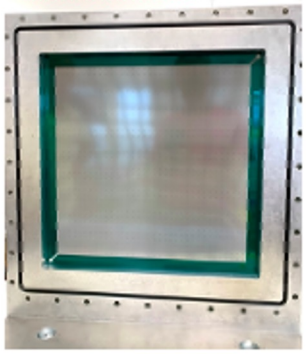


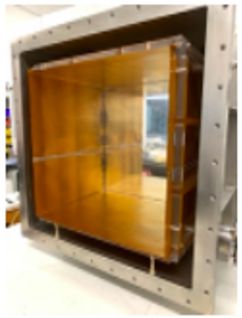
arXiv: 2304.08471 (published in APJ)

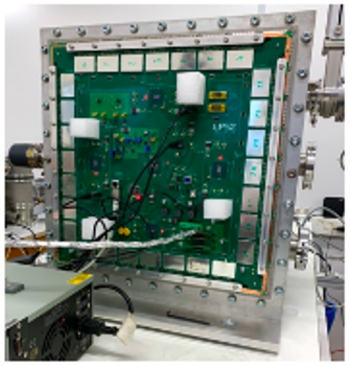
MIMAC

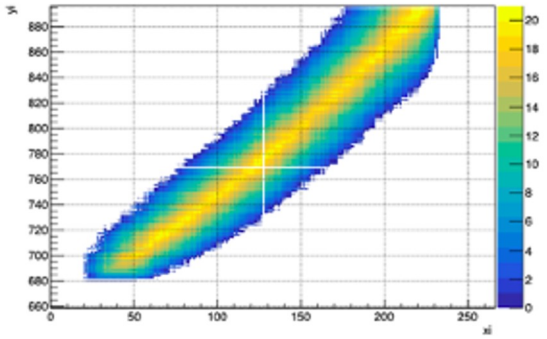
Daniel Santos – LPSC

The new **MIMAC** detector (35cm side, PCB, made at CERN) mounted and working in the bi-chamber at the LPSC-Grenoble



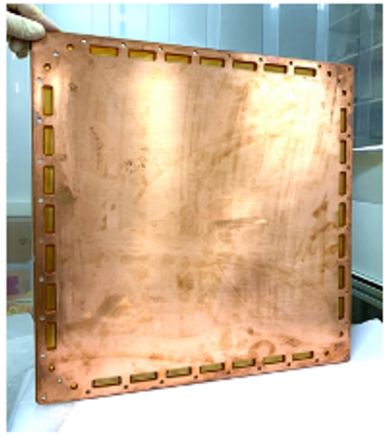






And the new Micromegas (35cm) on Kapton/Copper made by Chinese USTC team (Hefei)
With its Cooper interface

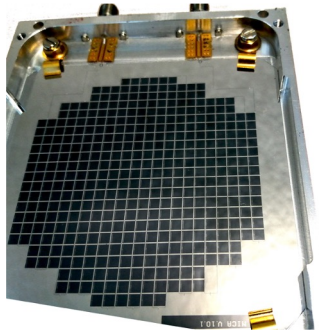
To be installed at LSM (March 2025)

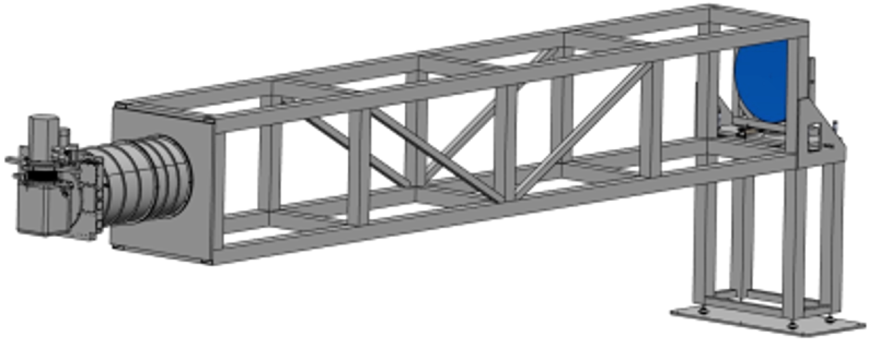


DArk photoN DirEctional detectION DANDELION at 1 meV

Daniel Santos – LPSC

418 pixels
Kid-Matrix





Experiment performed in October 2024
Data analysis in progress, Ilias Ourahou (PhD thesis) is working on

C. Beaufort, M. Bastero-Gil, A. Catalano, D-S. Erfani-Harami, J. Macias-Pérez, O. Guillaudin, D. Santos, S. Savorgnano, and F. Vezzu

C. Beaufort *et al*
JCAP06(2024)058

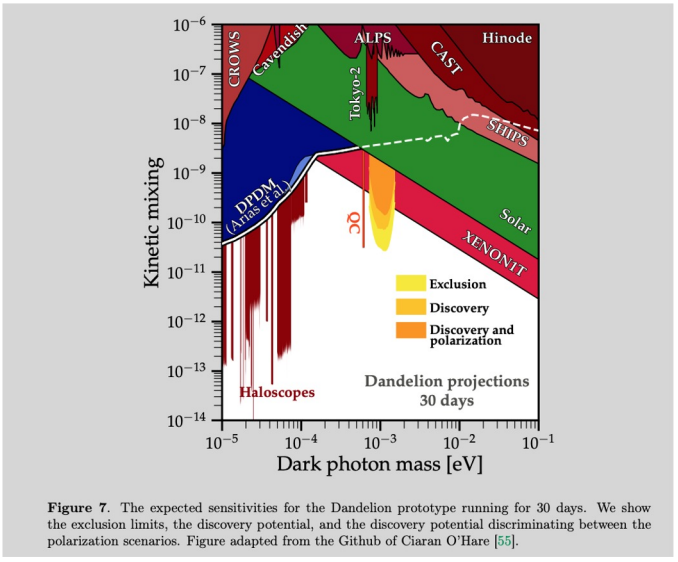


Figure 7. The expected sensitivities for the Dandelion prototype running for 30 days. We show the exclusion limits, the discovery potential, and the discovery potential discriminating between the polarization scenarios. Figure adapted from the Github of Ciaran O'Hare [55].

Search for light dark matter with NEWS-G at the LSM using a methane target

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(NEWS-G Collaboration)

arXiv:2407.12769
submitted to PRL

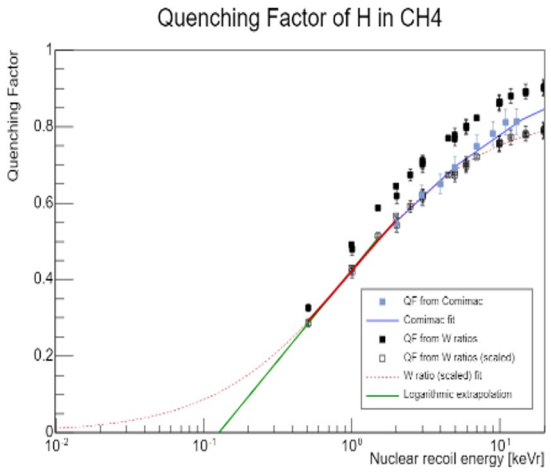


FIG. 1. QF used in this work. From highest to lowest energies, we use the COMIMAC measurement (lavender line [34]), scaled W-value ratios (red line [35]), and a logarithmic extrapolation (green line); the Lindhard-like extrapolation is shown for comparison (dotted red).

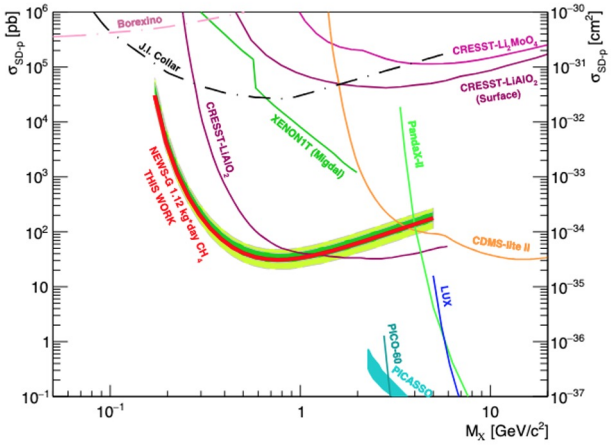


FIG. 3. Exclusion limit on the WIMP–proton spin-dependent cross section from this work (thick red line) and 1 and 2σ sensitivity bands (dark and light green shaded areas respectively). Upper limits from CDMS-lite [46], CRESST-III [47–49], LUX [50], PANDAX-II [51], XENON-1T (Migdal) [52], PICASSO [53], PICO-60 [54], J.I. Collar [55] and Borexino [56] are also shown.

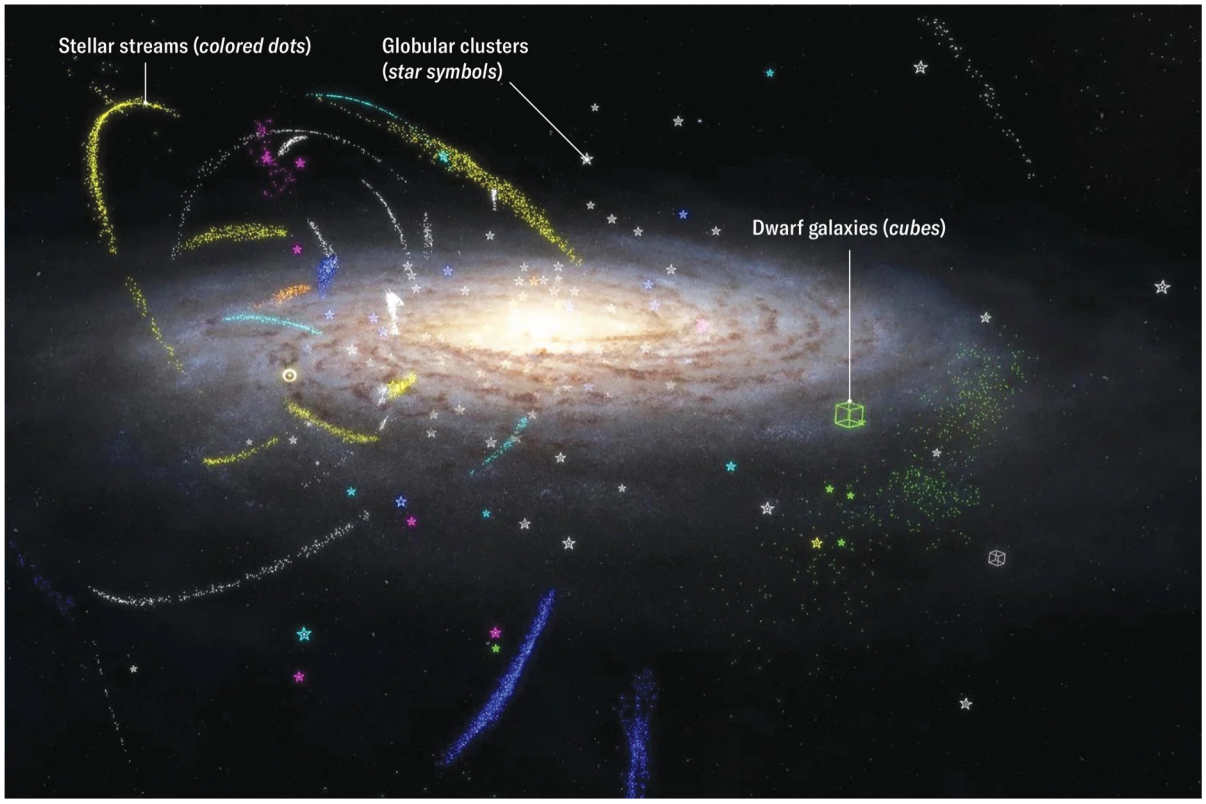
LSST - Steller stream project

Marine Kuna – LPSC

- Dark matter halos in the Milky Way using stellar streams detected by the Rubin Observatory/LSST
  PhD thesis of Matthieu Pelissier

- Impact of the systematic effects in LSST – Collaboration with Alex Drlica-Wagner

- Upcoming collaboration with Denis Erkal to enhance stellar streams in N-body simulations



Vue d'artiste de la Voie Lactée et de ses courants stellaires (points colorés), amas globulaires (symboles 'étoile') et galaxies naines sphéroïdes (petits cubes). © S. Payne-Wardenaar / K. Malhan, MPIA)