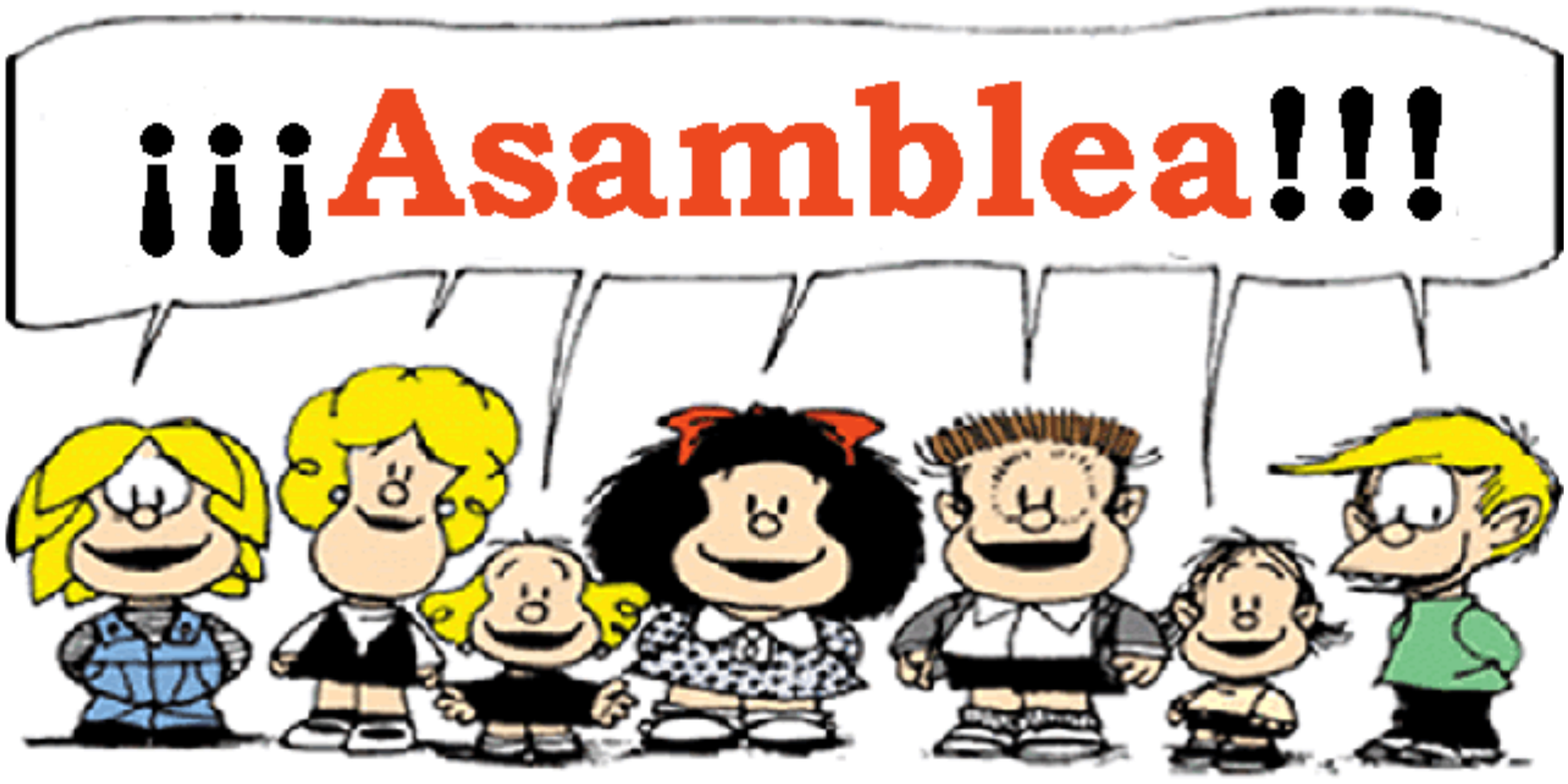
L4: Baryogenesis, dark matter and cosmic messengers

(a brief survey of topics studied at IFIC)

New name: Astroparticles, dark matter and cosmology



December 15, 2023

Coordinators:

Sergio Palomares, Óscar Vives and Juande Zornoza

L4: Baryogenesis, dark matter and cosmic messengers

at IFIC…

Matter-antimatter asymmetry

(mainly via leptogenesis)

collider and indirect
dark sector searches

Dark matter
(experiment and theory/phenomenology)

model building,
phenomenology
(cosmo, astro, colliders, etc.)

(mainly neutrinos)

Cosmic messengers
(from astrophysical sources)

(based on slides provided by a number of people)

Dark matter faces

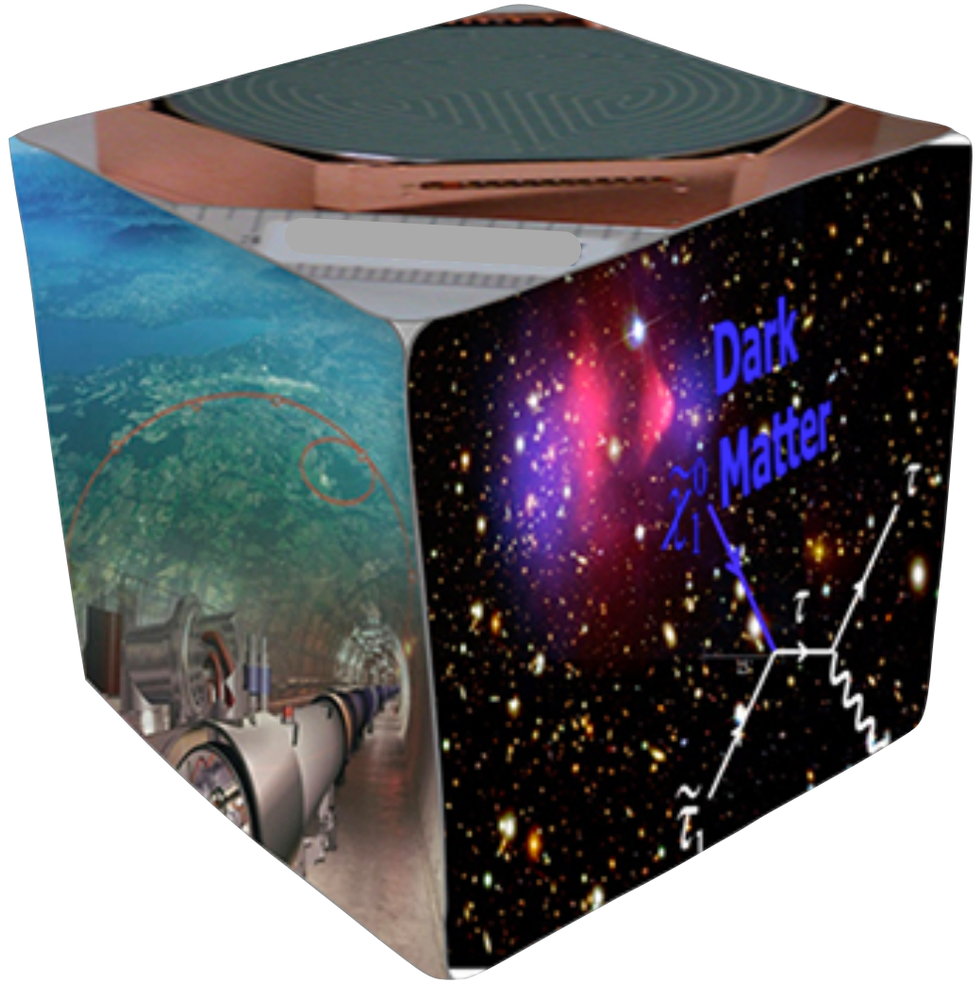
MODEL BUILDING AND PRODUCTION MECHANISMS

ASTRO/COSMO PROBES

BBN, CMB, 21cm, structure formation...

DIRECT DETECTION

Nuclear recoil produced by DM scattering



ACCELERATOR SEARCHES

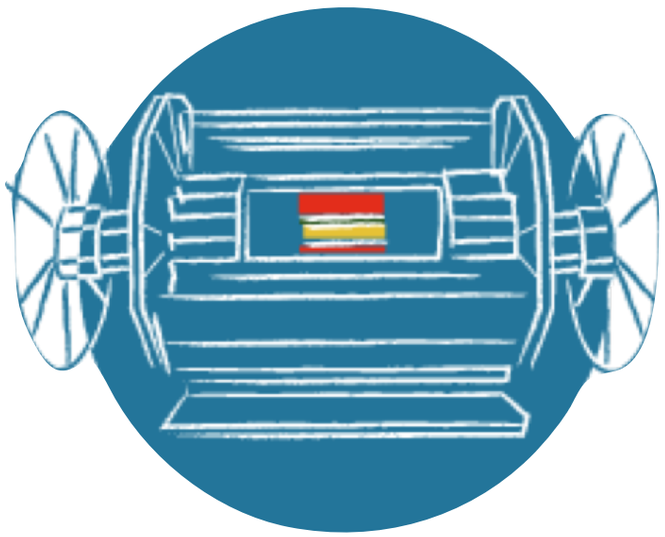
LLPs, Missing energy, mono-jets (bosons)

INDIRECT DETECTION

Products of DM annihilation/decay

Significant connections with other lines

Line 1: The Higgs Force



Line 2: Neutrinos and Lepton Flavour

Line 3: Flavor and Quark Matter

Line 5: Gravity and the Dark Universe: Gravitational Waves and Black Holes

Dark matter model building

Model building boils down to (properly) choosing...

Symmetry + Representations

DM stability **DM candidate**

In the process of making a DM model one should consider...

- Is the model compatible with the current constraints?
- Does the model address any other problem of the SM?
- Would a variation of the model lead to a different phenomenology?

MANY (really many) **models** ⇒ **Recent works just at IFIC** ⇒

- Scotogenic model (+ variants)
- DM from flavor or CP
- Supersymmetric DM
- DM from extra dimensions
- DM related to lepton number

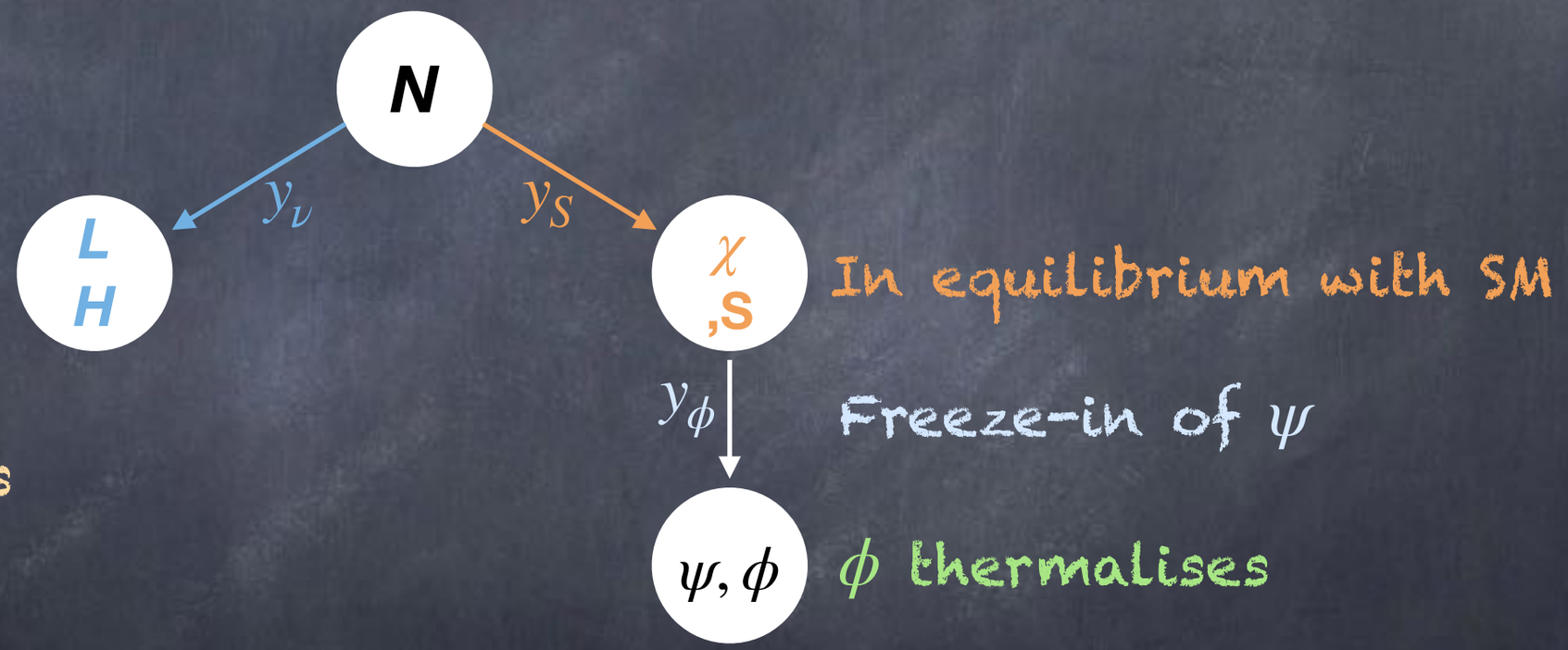
Dark matter in the light of no signals

Well-motivated DM models with suppressed signals are needed:
PNGB DM, annihilations into ν_R, multi-DM, asymmetric freeze-in...

extended cogenesis framework

[G. Landini, JHG, D. Vatsyayan, JHEP05 (2023) 049]

$$\mathscr{L}_{\rm int} = -y_\nu^{\alpha i}\,\bar{L}^\alpha \tilde{H} N_R^i - y_\sigma^{ij}\,\sigma \overline{N_R^{ic}} N_R^j - y_S^i\, S \bar{N}_R^i \chi - y_\phi\, \phi \bar{\psi} \chi + \text{H.c.}$$



$$m_\nu \simeq -\, y_\nu \frac{v^2}{M_N} y_\nu^T$$

$\Delta L \to \Delta B$: sphalerons

Idea: Dark asymmetry transferred via late decays
$\chi \to \psi + \phi$, after χ symmetric population has been erased

We consider $\eta_\chi \equiv \eta_D \simeq \eta_B$

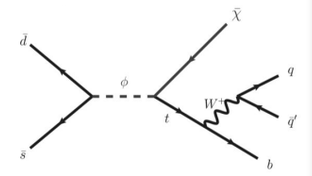
(searches of long-lived weakly interacting particles also at MoeDAL, LHCb, NA64)

Search for invisible particles produced in association with single top quarks

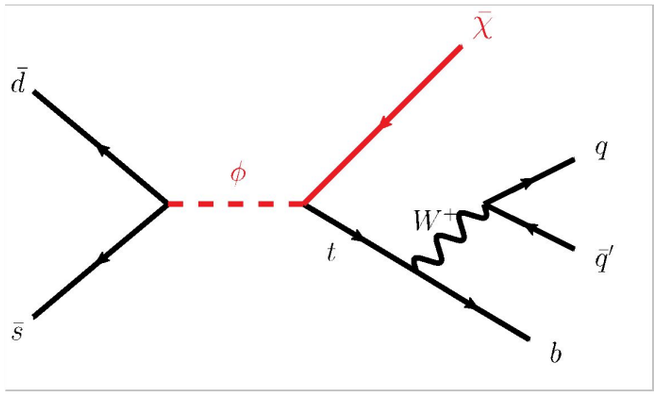
- Looking at signatures of a top + invisible with the full Run-2 dataset.
- All-hadronic channel considered.
- Focused on models:
  - Dark Matter (DM) Monotop model (scalar and vector DM mediators).
  - Vector-like top production.

Simplified models

- Signature-driven first-order description of new physics.
- Bridge gap between EFT and complete models.



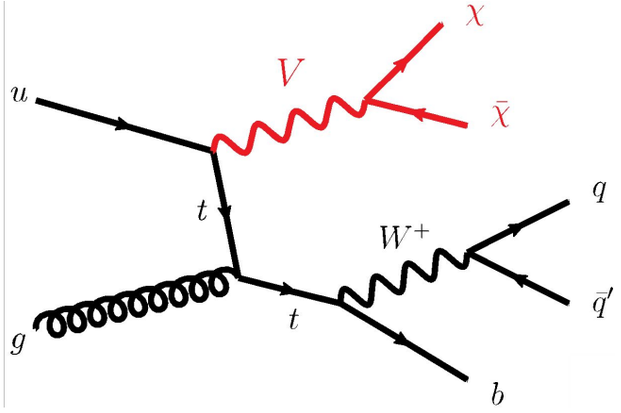
Scalar DM mediator



Colored-charged scalar decaying to a top quark and a DM particle.

Parameters:
- Couplings λ_q and y_χ.
- Masses of the mediator ϕ and the DM particle χ.

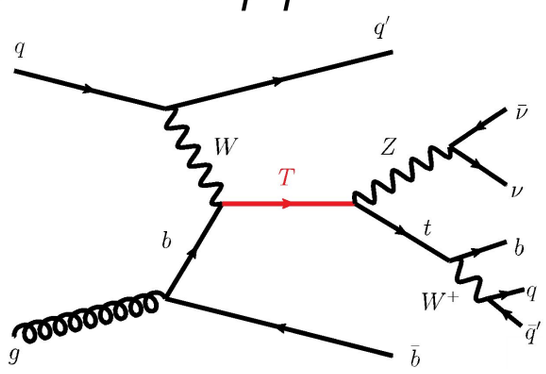
Vector DM Mediator



FCNC interaction between *u* and top quarks and a vector mediator, which further decays to a couple of DM particles.

Parameters:
- Couplings a and g_χ
- Masses of the mediator V and the DM particle χ.

Vector-like top production



Here focused on the single Vector-Like Top production, considering the invisible decay of the Z boson. Additional forward jet is expected.

Parameters:
- Overall coupling κ_T (related to W, Z and H couplings).
- Mass of the VLT.

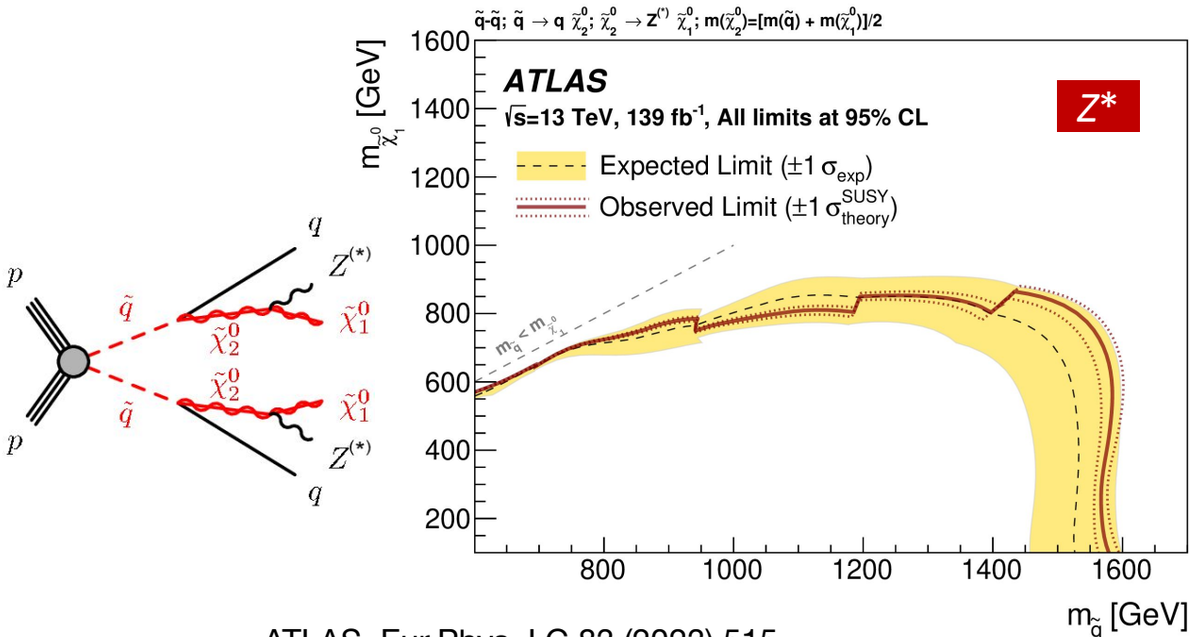
And also…

Search for dark matter produced in association with single top quark and an energetic W-boson

Search for neutral long-lived particles that decay into displaced hadronic jets in the ATLAS calorimeter

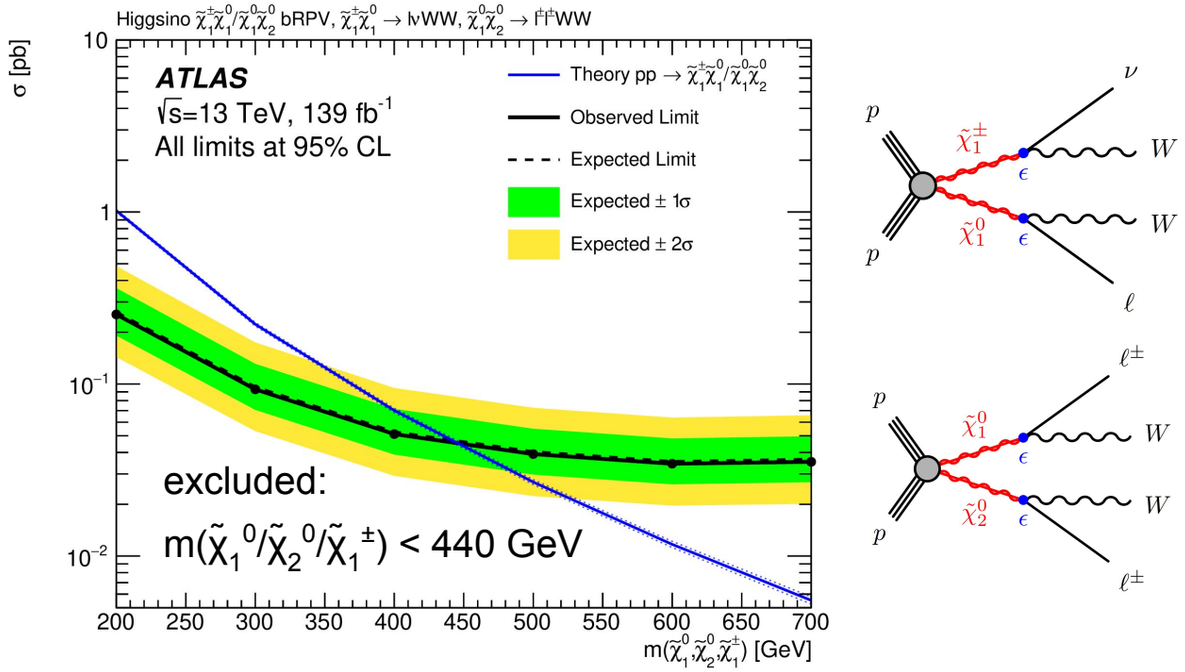
SUSY searches

- Peak or edge in $m_{\ell\ell}$ distribution
- Exclude regions of SUSY mass parameter space by "stitching" SRs
- Also considered electroweakino production



ATLAS, Eur.Phys.J.C 83 (2023) 515

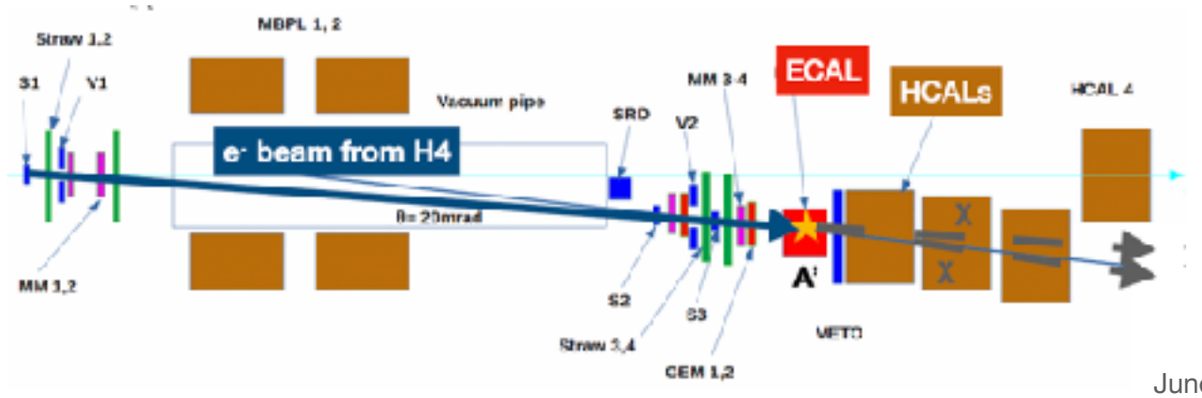
- Final state with 2 same-sign or 3 leptons
- **Bilinear R-parity violation** (bRPV)
- Higgsino lightest SUSY partner
- First constraints on bRPV in electroweak production!



- IFIC: Analysis contact & contact editor

ATLAS, JHEP 11 (2023) 150

NA64: *Latest results on Light Dark Matter*



Editors' Suggestion

Search for Light Dark Matter with NA64 at CERN

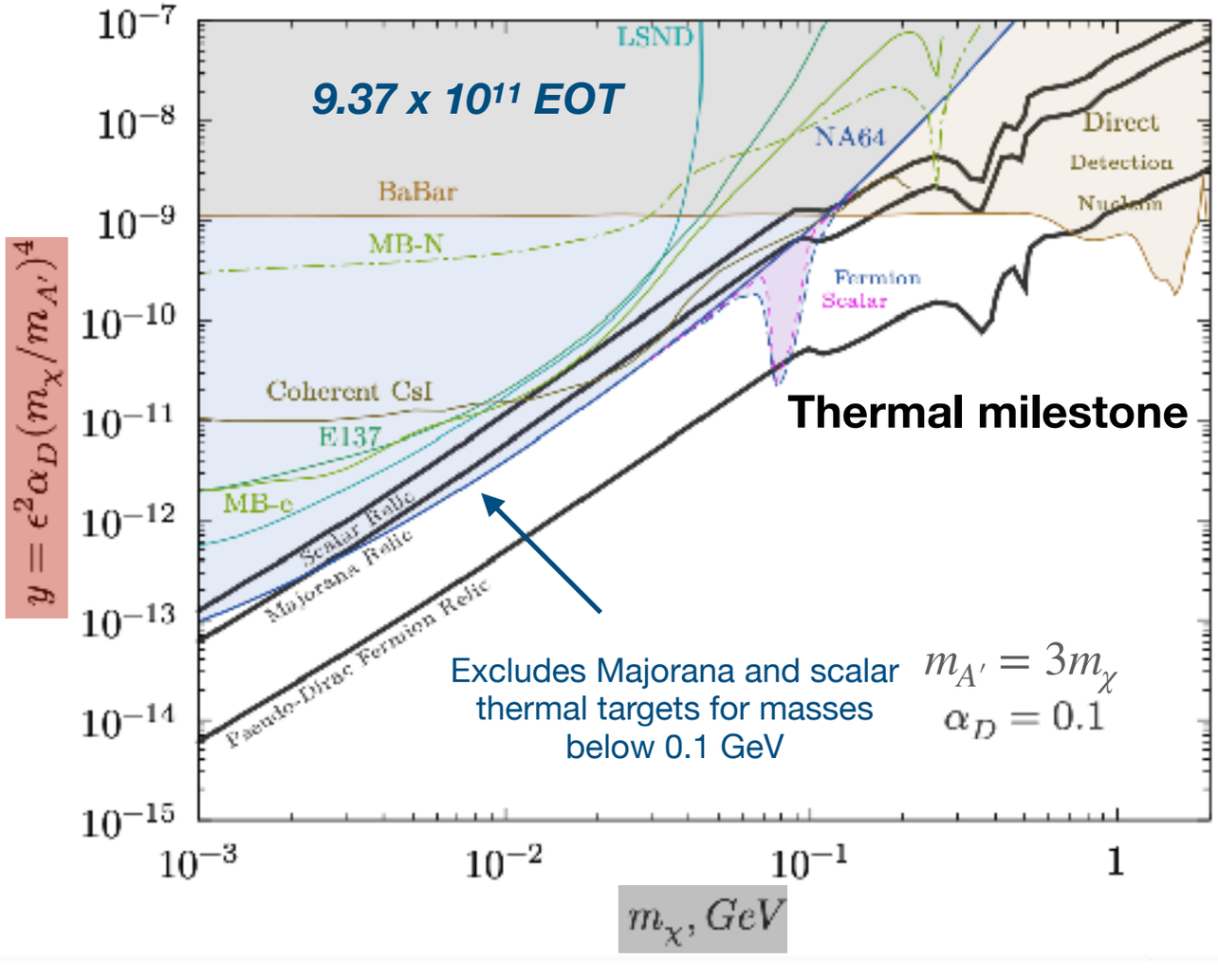
Yu. M. Andreev *et al.* (NA64 Collaboration)

Phys. Rev. Lett. **131**, 161801 (2023) – Published 16 October 2023

An experiment at CERN performed by scattering 100 GeV electrons off a fixed target results in limits on thermal dark matter—that requires interactions mediated by hypothetical dark photons—in the MeV mass range.

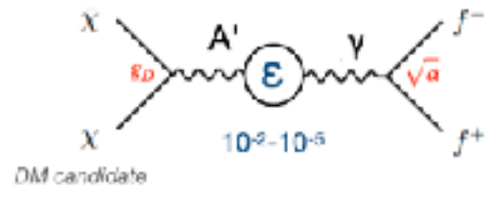
Show Abstract +

June 2023 CERN EP Newsletter: https://ep-news.web.cern.ch/content/lighting-dark-na64-news-light-dark-matter-searches



Thermal milestone

$$\Omega_\chi \propto \frac{1}{<\sigma v>} \sim \frac{m_\chi^2}{g_\chi^4}$$



$$\sigma v(\chi\chi \to A' \to ff) \propto \epsilon^2\alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2}$$

A' → $\chi\bar{\chi}$: NA64 Results start probing for the first time the LDM benchmark model parameter space

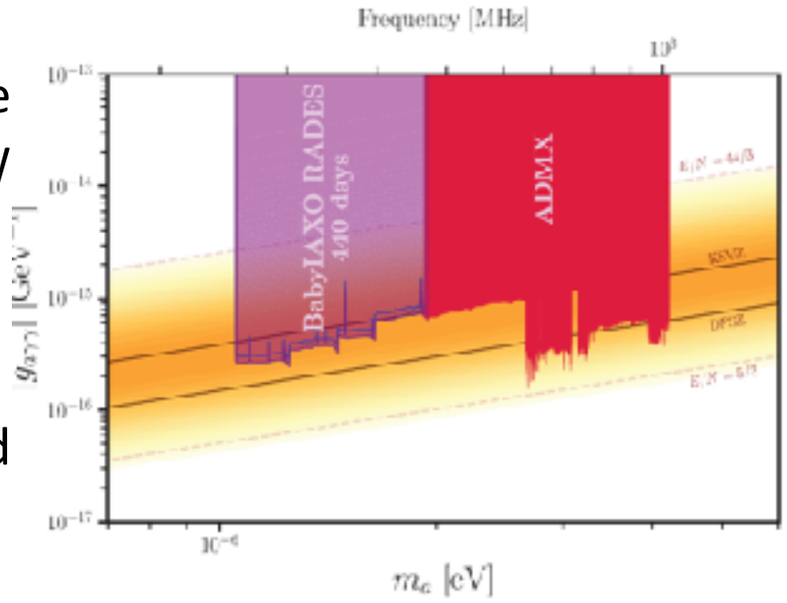
Dark matter axions (not only the QCD axion) and gravitational waves search using microwave and millimeter-waves cavities

AITANA

GENERALITAT VALENCIANA

- **Detection of dark matter axions with microwave and millimeter-waves haloscopes:**
  - ✓ Development of full-wave advanced modal techniques for the rigorous and accurate analysis of the coupling between the axions and the resonant modes of the cavities (axion-photon coupling).
  - ✓ Electromagnetic design of different resonators for detection in three frequency bands: UHF-VHF bands (300 MHz), X band (8 GHz) and W band (90 GHz)
  - ✓ Participation in three international collaborations:
    - RADES (Relic Axion Detector Exploratory Setup) at CERN (X-band)
    - CADEx (Canfranc Axion Detection Experiment) at Underground Laboratory of Canfranc, Huesca (W band)
    - Baby-IAXO (International Axion Experiment) at DESY (UHF-VHF bands)
- **Detection of High-Frequency Gravitational Waves (HF-GW) in the microwave frequency band.**

Baby-IAXO sensitivity

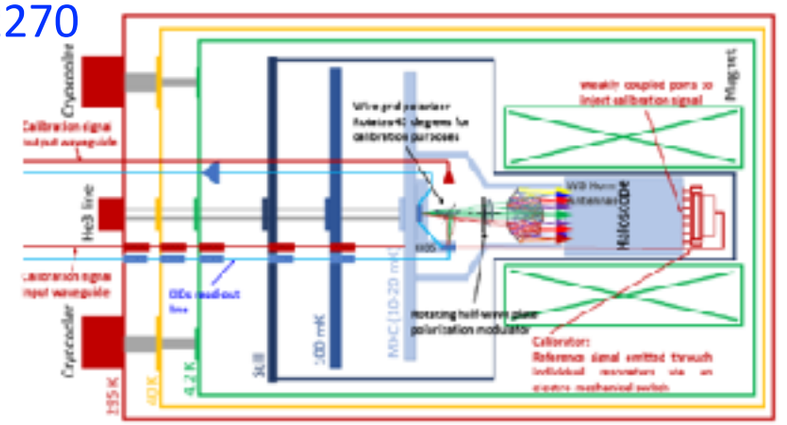


Some recent works by IFIC people:

V. Domcke, C. Garcia-Cely, S. M. Lee and N. L. Rodd, arXiv:2306.03125

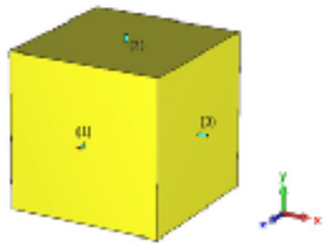
P. Navarro, B. Gimeno, J. Monzón-Cabrera, A. Díaz-Morcillo and D. Blas, arXiv:2312.02270

Scheme of the CADEx experiment



RADES cavity

Cubic resonator for HF-GWs exploration

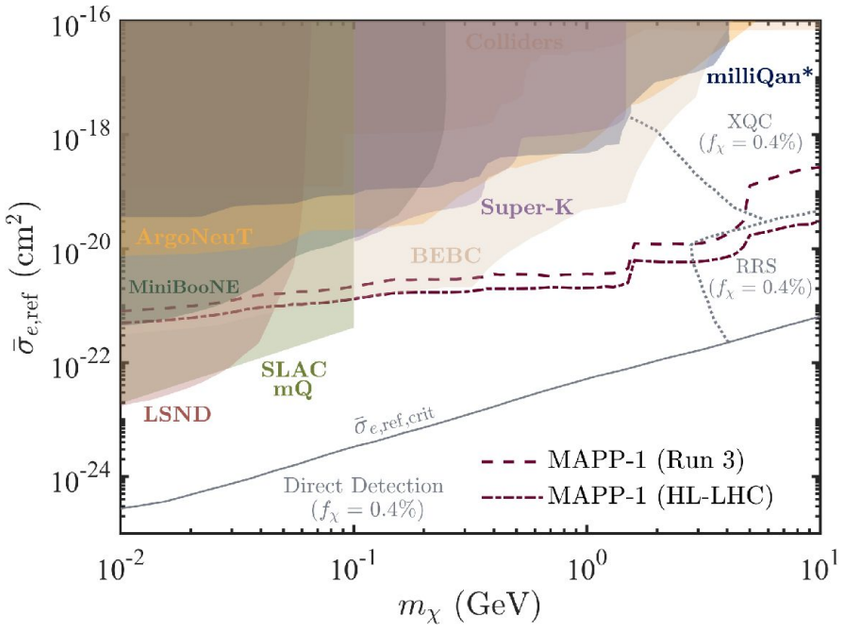


Other searches for exotic physics

MoEDAL

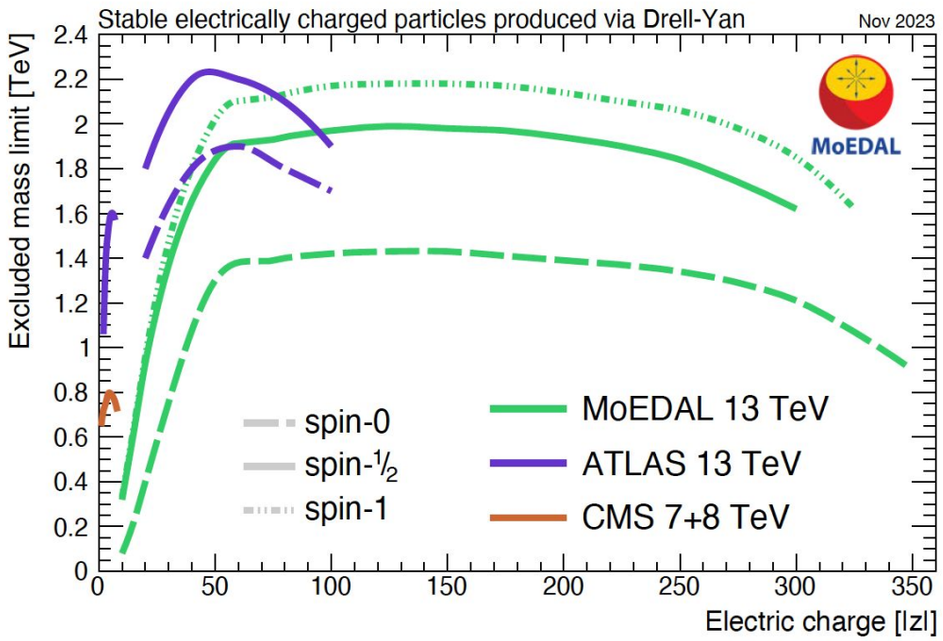
AITANA

- Prospects for detecting millicharged particles @ MAPP
- Strongly interacting DM



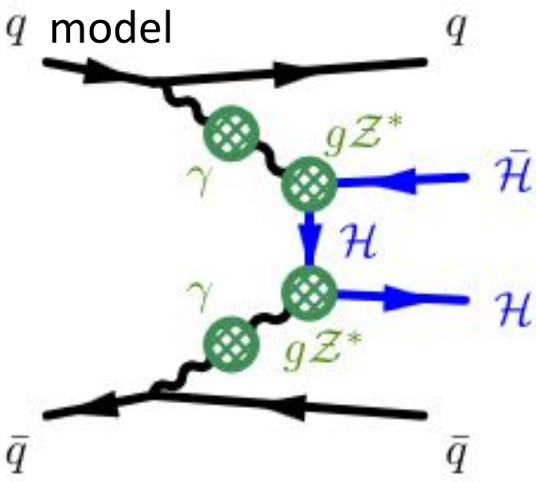
Mitsou, Montigny, Mukhopadhyay, Ouimet, Pinfold, Shaa, Staelens, arXiv:2311.02185 [hep-ph], submitted to JHEP

- Full Run-2 MoEDAL analysis
- Magnetic monopole sensitivity to **10 Dirac charges**
- Electric charges up to **350e**
- Highest charges probed in colliders!



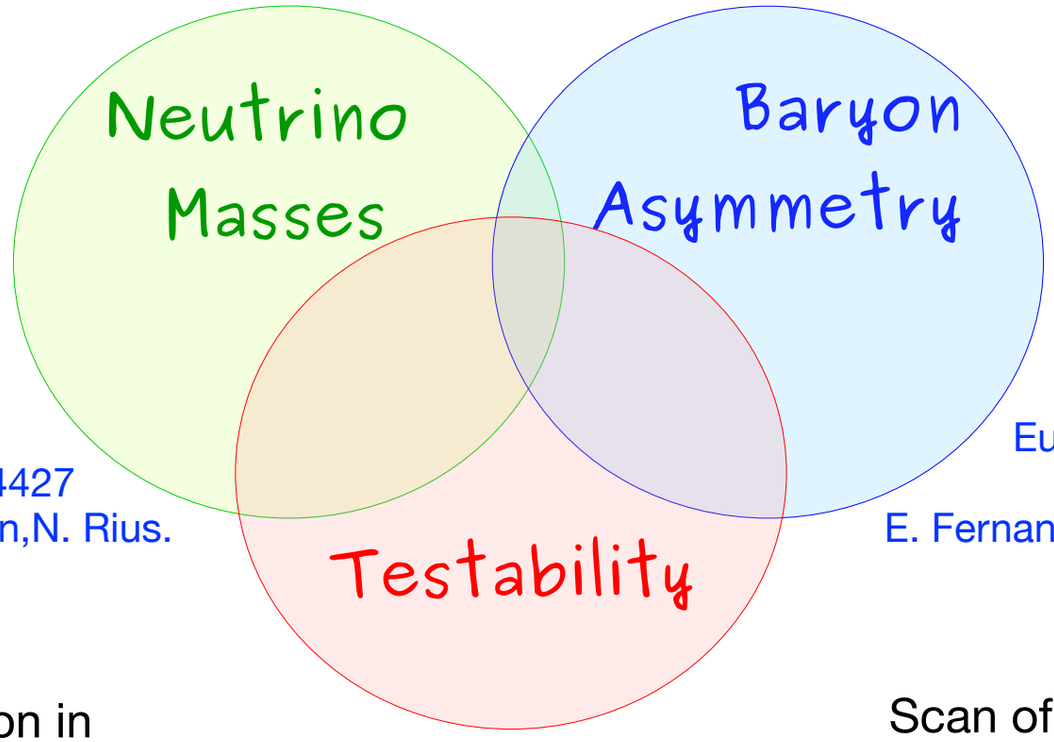
MoEDAL, arXiv:2311.06509 [hep-ex], submitted to PRL

- Resummation Dyson-Schwinger on high-electric-charge particles to tackle large (non-perturbative) couplings to photons and Z bosons
- Implemented in MadGraph via UFO model



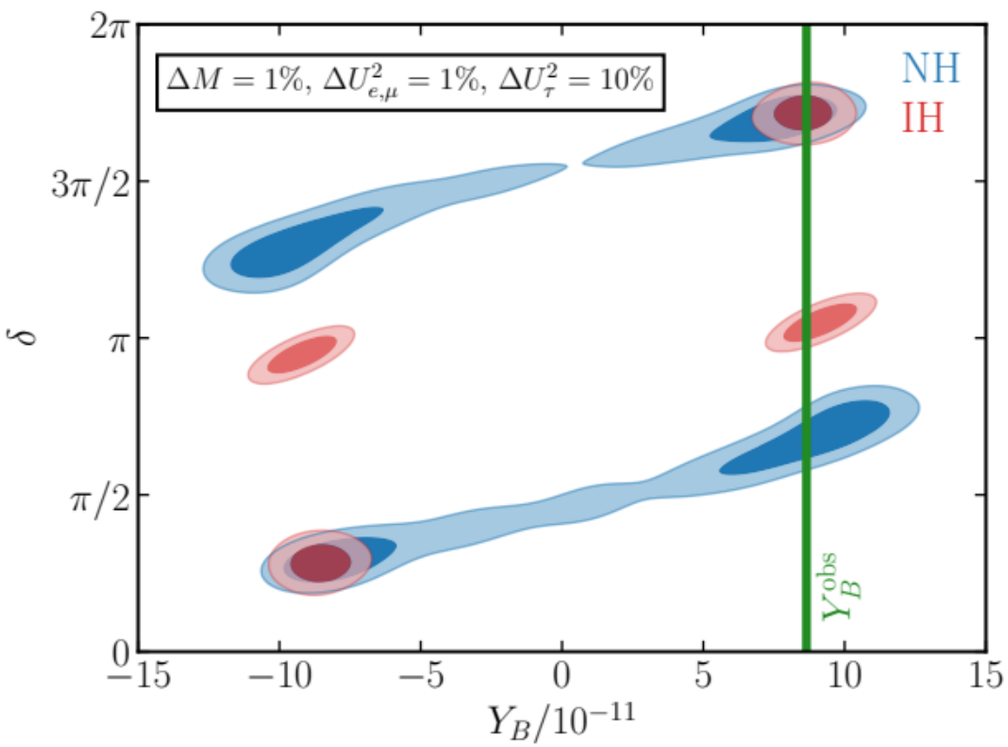
Alexandre, Mavromatos, Mitsou, Musumeci, arXiv:2310.17452 [hep-ph], submitted to PRD

Musumeci, LHCP2023



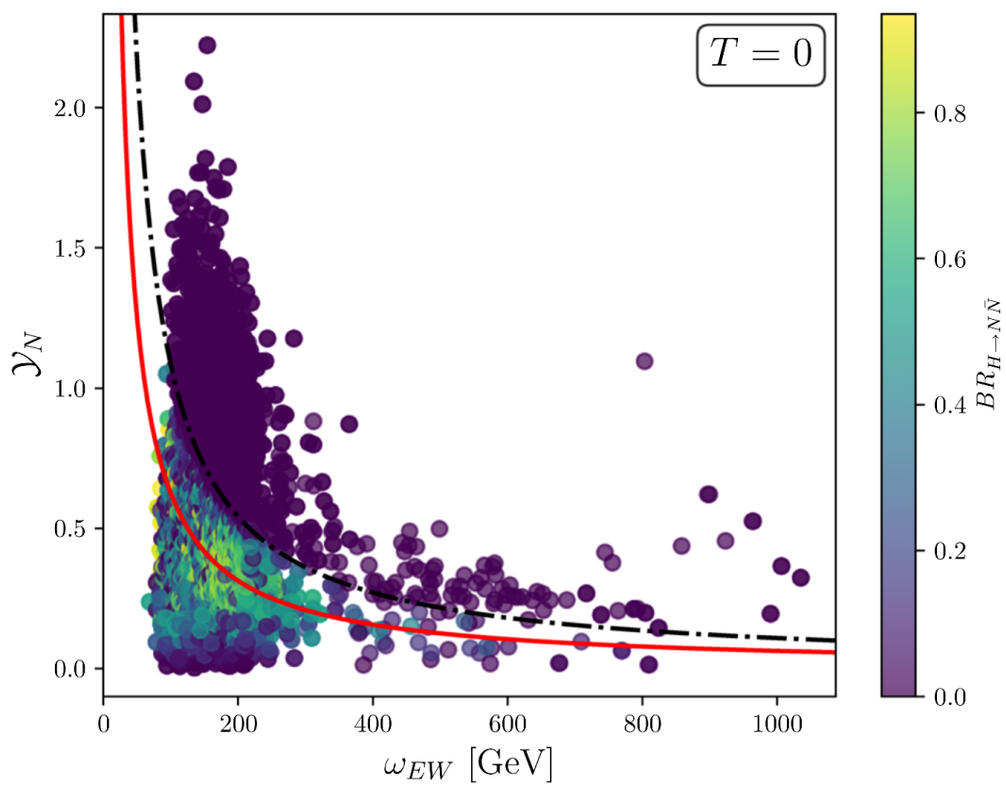
JHEP 11 (2023), 153. ArXiv:2305.14427
S. Sandner, P. Hernandez, J Lopez-Pavon,N. Rius.

Measurement of CP violation in neutrino oscillations, HNLmasses and mixings with electron, muon and tau flavours can suffice to pin down matter-antimatter asymmetry from laboratory measurements.



Eur. Phys. J. C 83 (2023) no.8, 715.
ArXiv:2210.16279
E. Fernandez-Martinez, J. Lopez-Pavon, J.M. No, T. Ota and S. Rosauro-Alcaraz

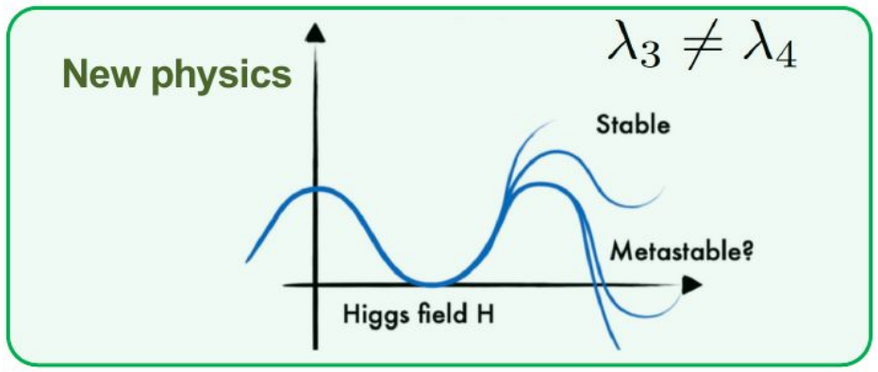
Scan of the parameter space of general singlet scalar BSM extension to identify regions which can lead to strong first-order phase transition, as required by electroweak baryogenesis, taking into account bubble nucleation as fundamental constraint.



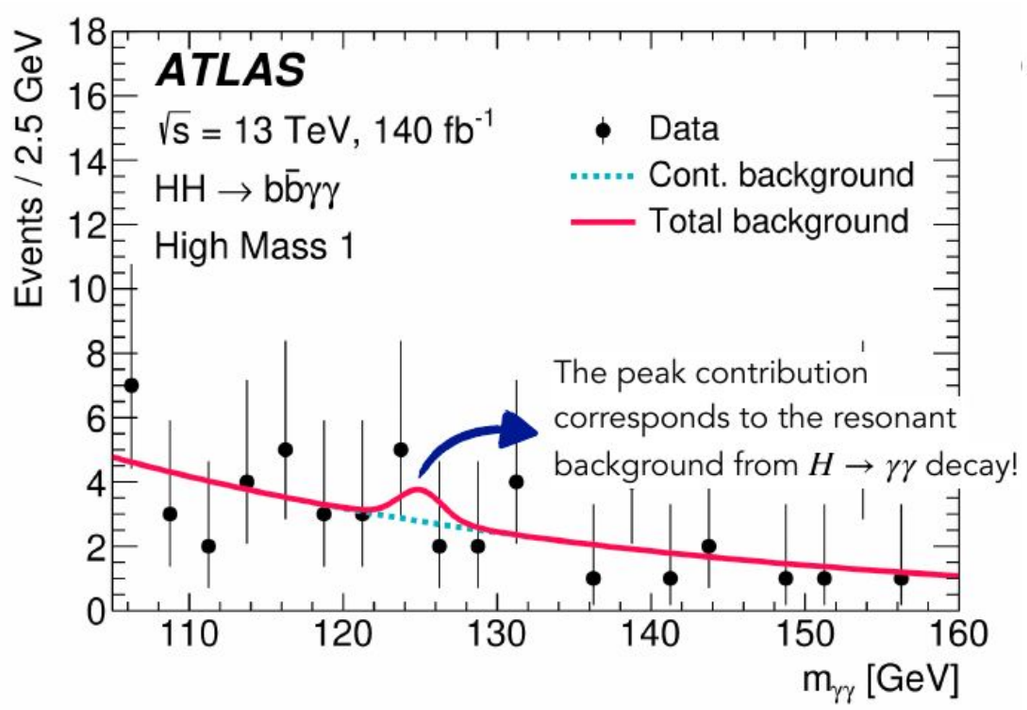
Search for Higgs boson pair production in the bbγγ final state with the ATLAS detector

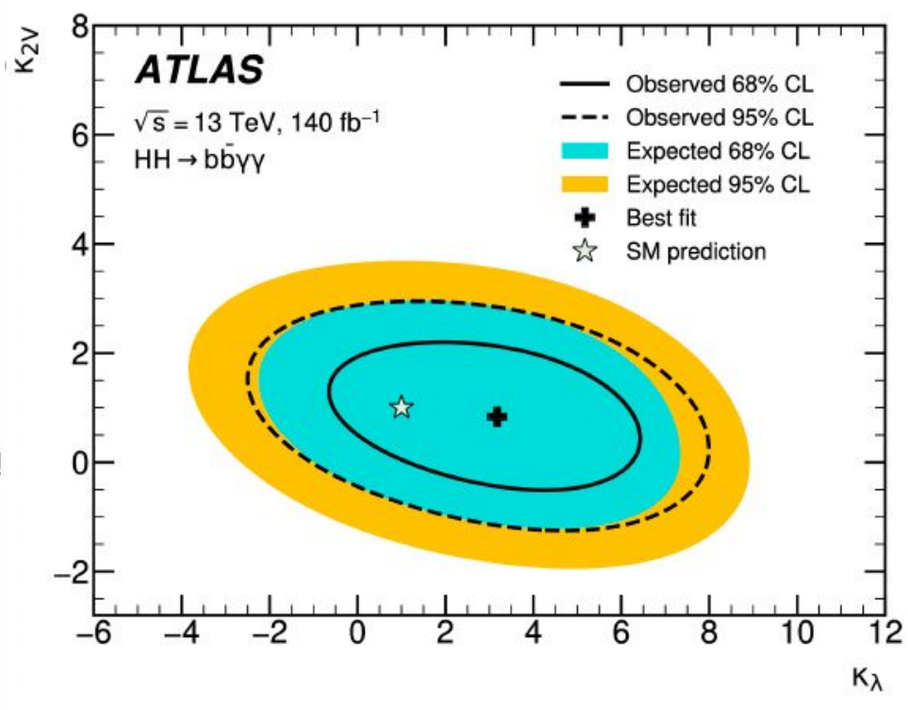
https://arxiv.org/abs/2310.12301

- Shape of the Higgs potential together with m_H can have big consequences for the Universe.
- Searching for Higgs boson pair production constitutes the only direct probe to trilinear Higgs self coupling (k_λ), linked to the the Higgs potential shape.
- The $b\bar{b}\gamma\gamma$ is one of the golden channels for HH searches: Large $H \rightarrow b\bar{b}$ branching fraction + very clean di-photon signature.



- No deviations from SM found, but constraints on self coupling are getting closer to SM expectation.
- Effective Field Theory coefficients constrained too.

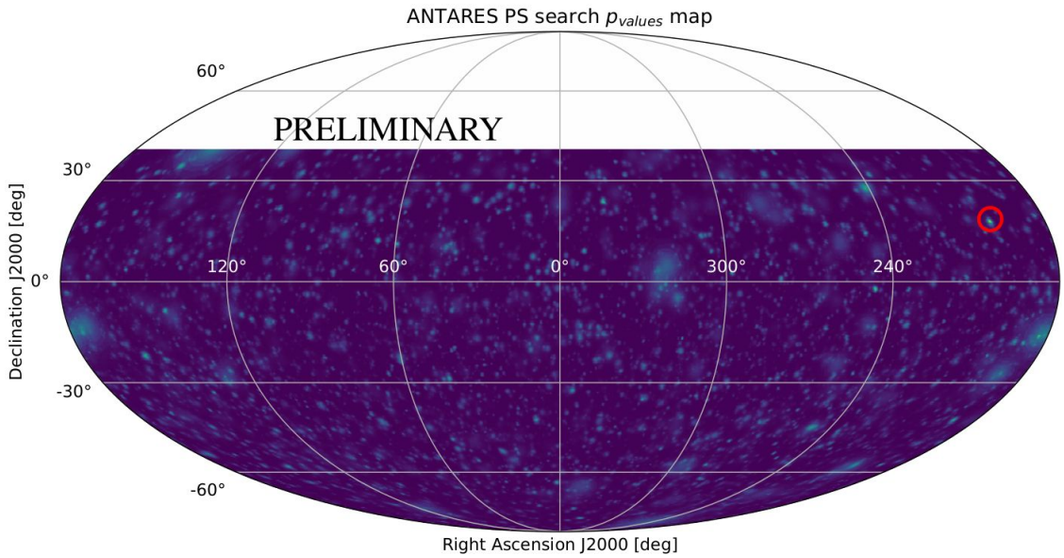




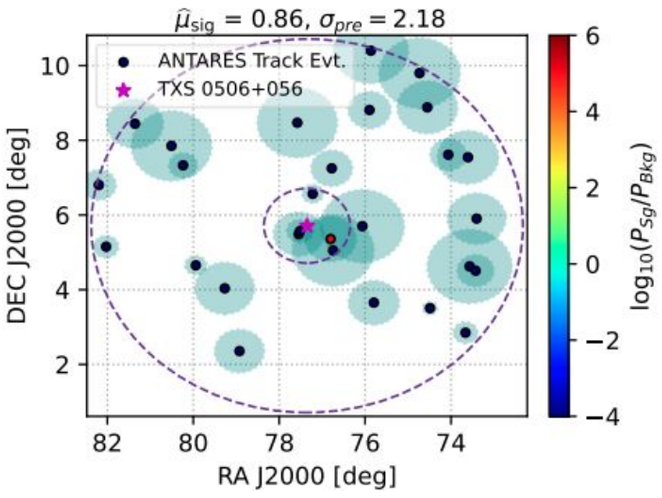
ANTARES: Search for cosmic neutrino sources

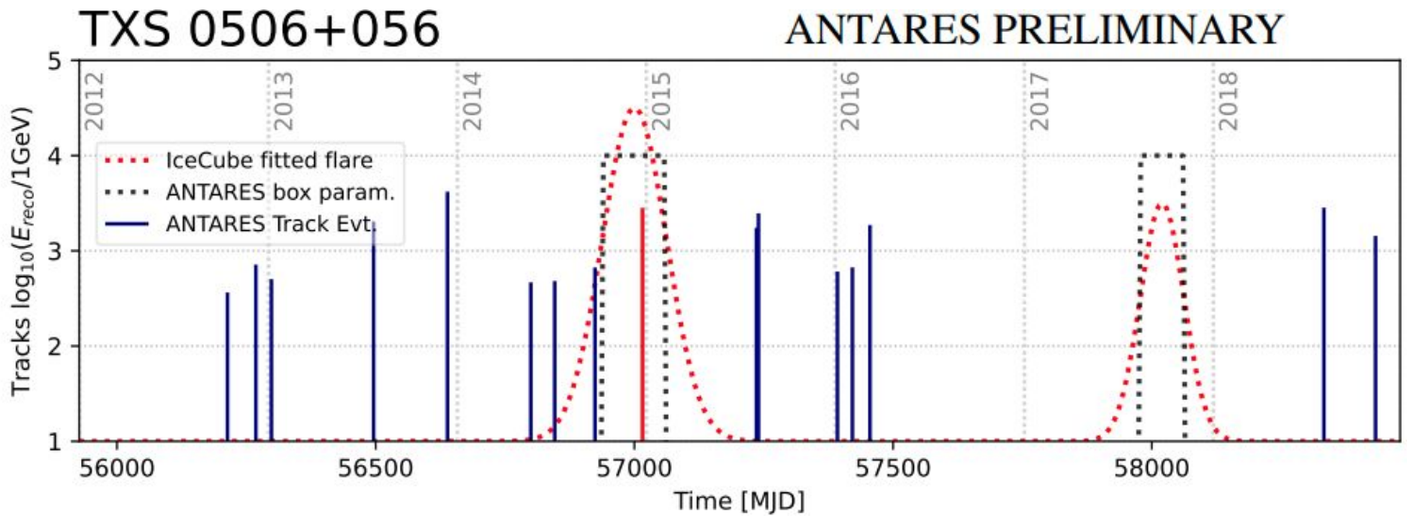
- **ANTARES** decommissioned in 2022: **final analyses being published**.
- IFIC led the **search for cosmic neutrino sources**, both time-integrated and time-dependent [**S. Alves**, F. Salesa, A. Sánchez].
- Best candidates compatible with background fluctuations.
- Some **interesting upper fluctuations** observed:
  - **TXS0506+056** in the “top 5” most promising candidates (2.4σ).
  - Neutrino event compatible with TXS0506+056 detected in time coincidence with a flaring period reported by IceCube (2.2σ).

PoS ICRC 2023 (1128)



PoS ICRC 2023 (1480)



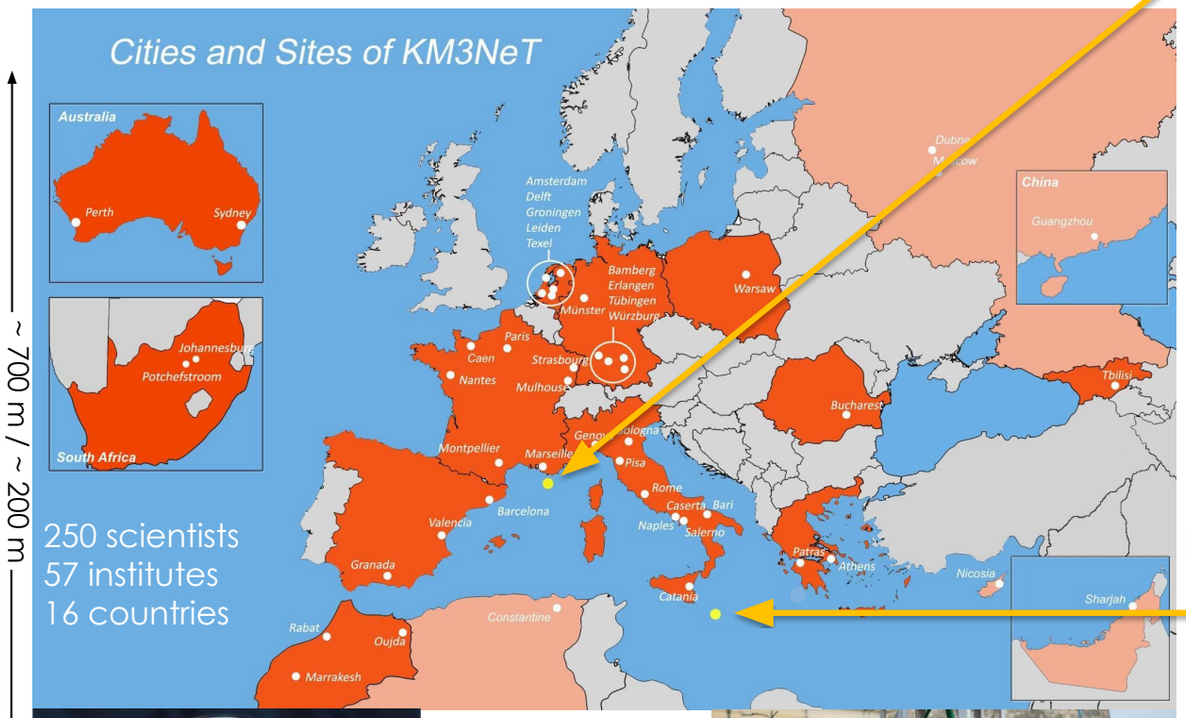


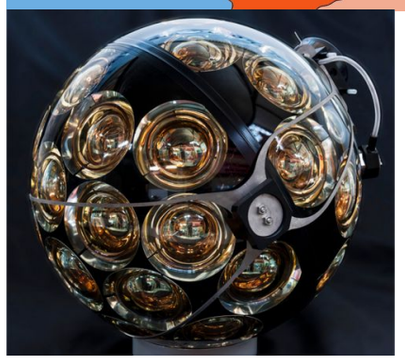
KM3NeT

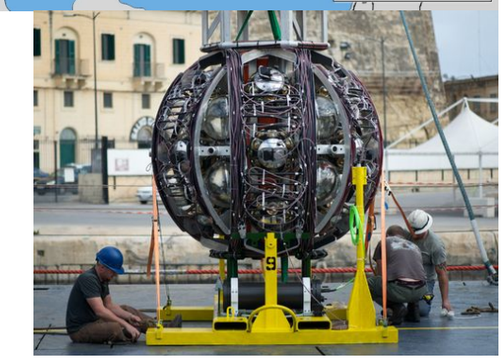
Multi-site, deep-sea infrastructure

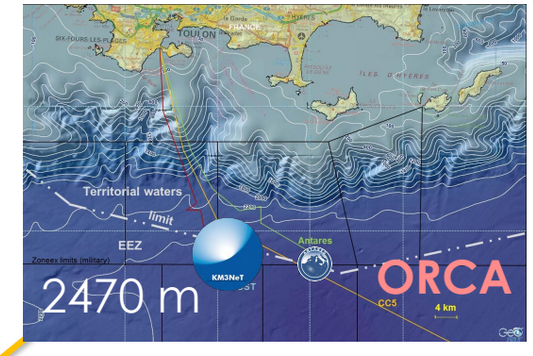
Single collaboration, Single technology

Two outstanding physics cases



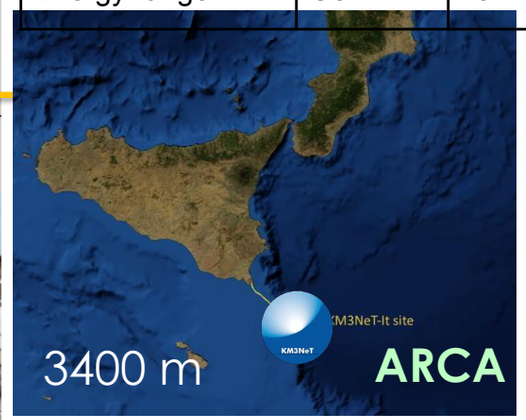




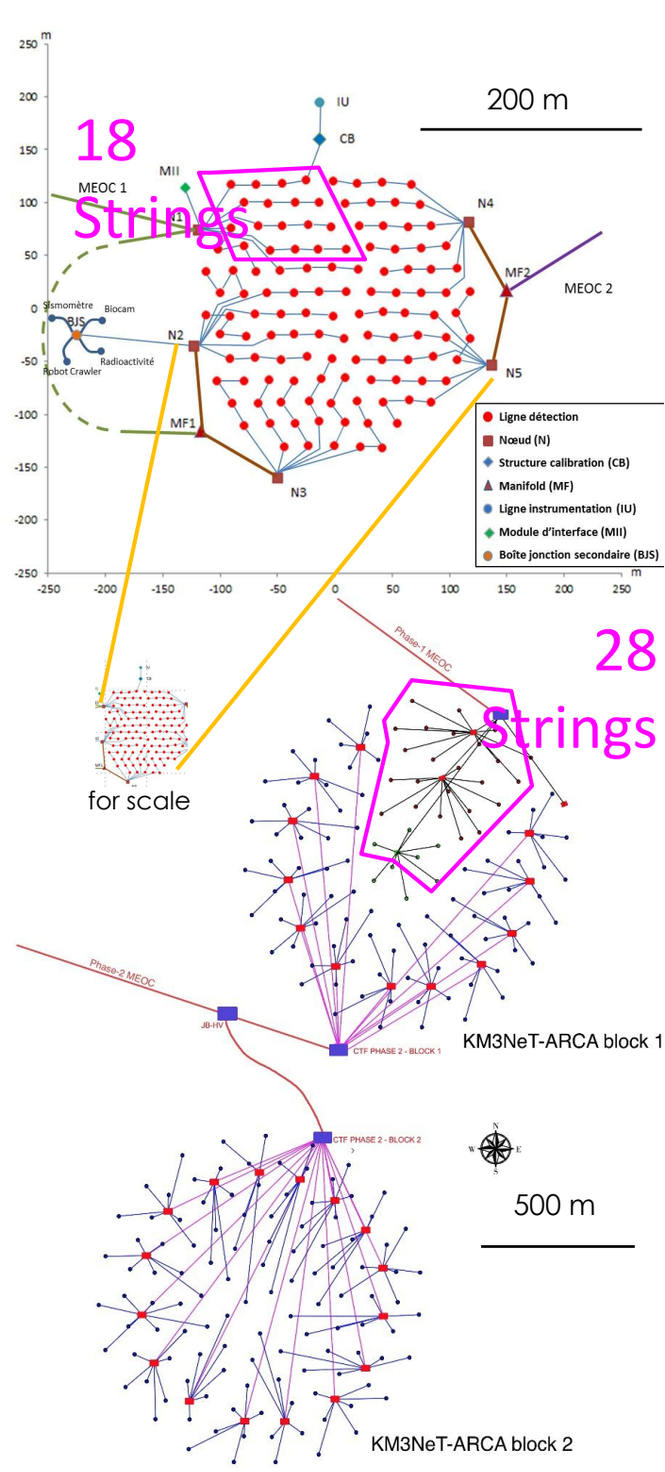


Oscillation Research with Cosmics in the Abyss

	ORCA	ARCA
Strings	115	115 × 2
String spacing	20 m	90 m
DOM spacing	9 m	36 m
Instrumented mass	7 Mton	500 × 2 Mton
Energy range	GeV	TeV – PeV



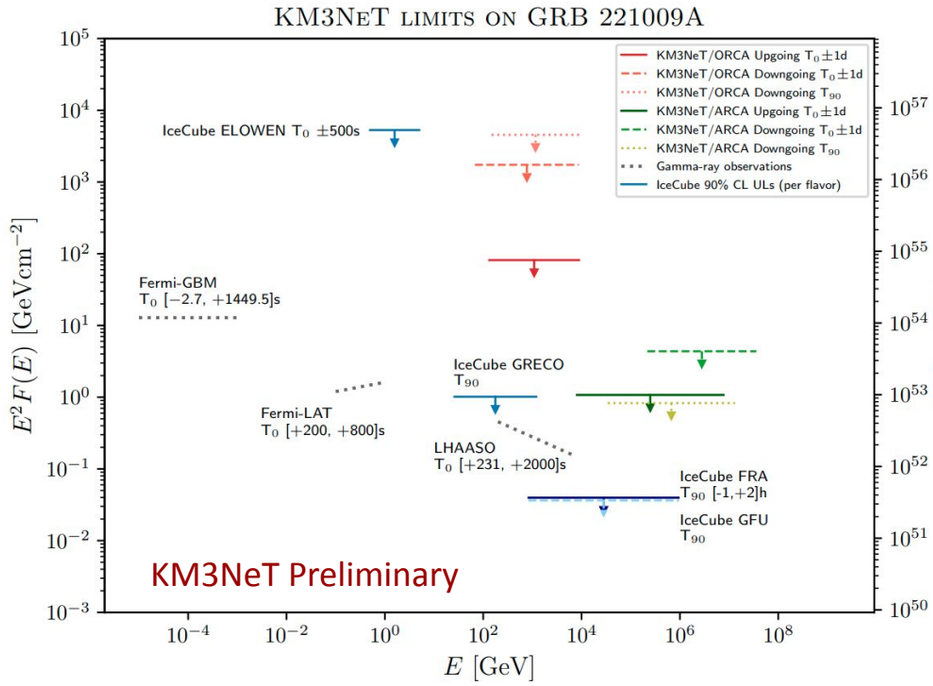
Astroparticle Research with Cosmics in the Abyss



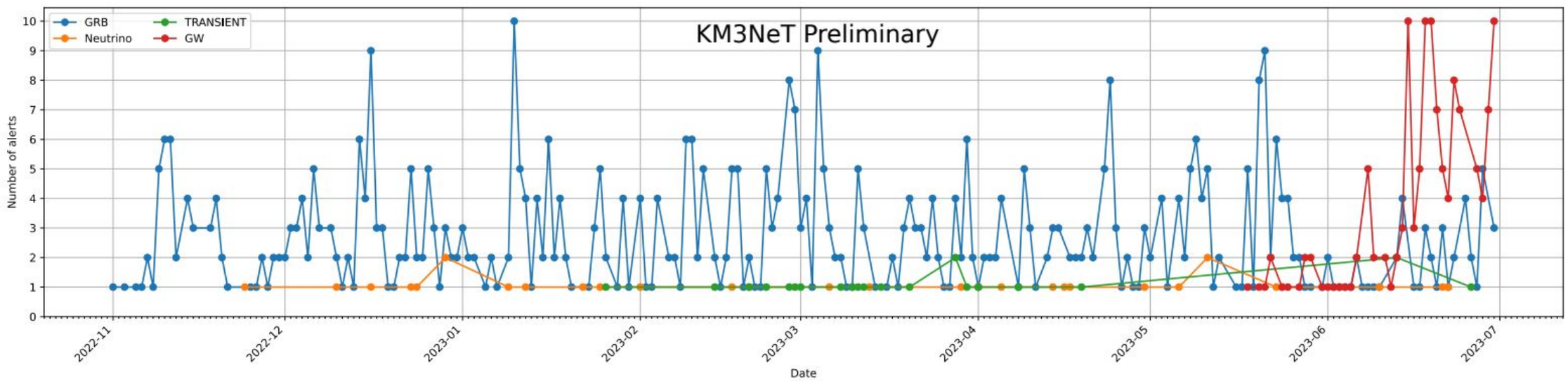
KM3NeT: Search for cosmic neutrino sources

- ANTARES upper fluctuations mean **KM3NeT potential for discoveries**.
- IFIC deeply involved in **cosmic neutrino source searches**:
  - Time-dependent searches [**E. Pastor**, AS].
  - Transients searches: **GRB 221009A** (brightest GRB ever detected) [**J. Palacios**, FS, AS].
  - Real-time transient searches [**JP**, **V. Cecchini**, FS].
  - Development of the “Online Analysis Framework” for multi-messenger astronomy [**VC**, **JP**].

PoS ICRC 2023 (1503)



PoS ICRC 2023 (1521)



Using other messengers (gamma rays) for point-source searches

Deepening gamma-ray point-source catalogues with sub-threshold information

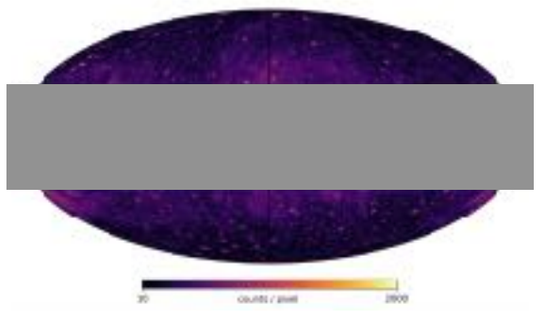
Aurelio Amerio, Francesca Calore (Annecy), Pasquale Serpico (Annecy), Bryan Zaldívar arXiv: 2306.16483

Idea: Providing a "probabilistic catalog" of gamma-ray sources going also below the current Fermi-LAT sensitivity

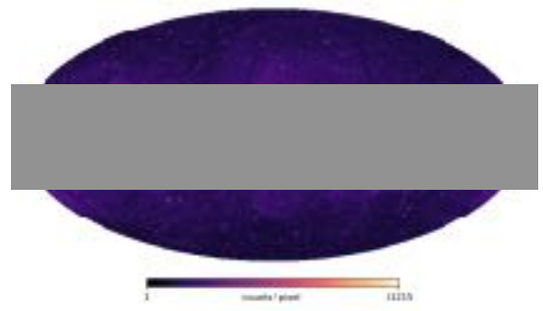
Methodology

- Gamma-ray sky map simulator using a source count distribution dN/dS given by a pre-trained ML model (Amerio et al, 2302.01947)

- Comparing the measured map with simulated maps

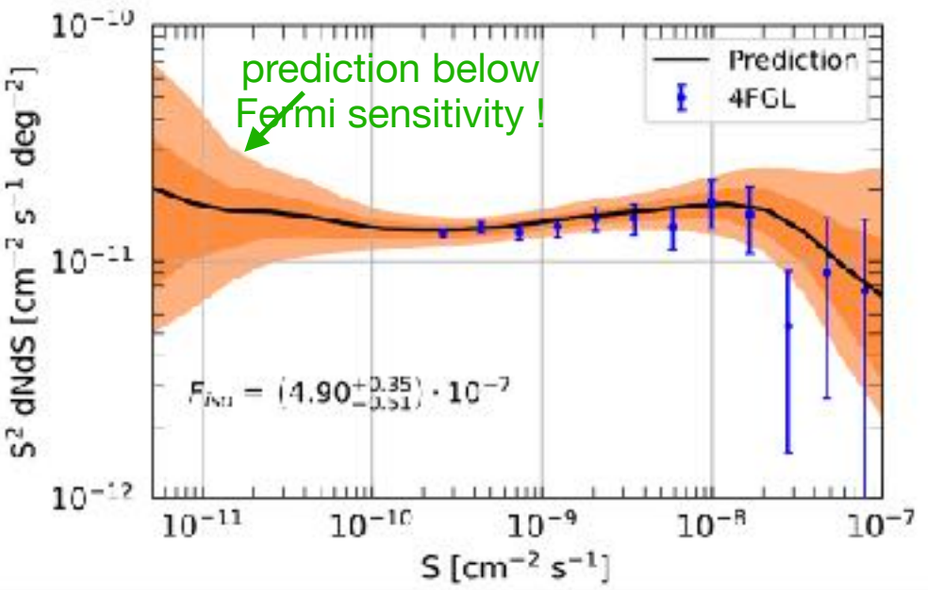


A simulated sky



The measured sky (Fermi-LAT)

- $\mathrm{TS}_i = \dfrac{(x_i - \lambda_i)^2}{\lambda_i}$ A distribution of test-statistic for pixel i, comparing simulated/measured count x_i with diffuse model prediction λ_i



(Latest Fermi-LAT catalog contains ~6000 point sources)

- TS-distribution of simulated sky and measured sky compatible up to a certain threshold TS_* according to Kolmogorov-Smirnov test

- Fermi sky pixels having $\mathrm{TS} > \mathrm{TS}_*$ are candidates of new sources (even below Fermi sensitivity)

Results

Public code available on GitHub: delivers a source catalog on demand for a given confidence level and source reliability (QF)

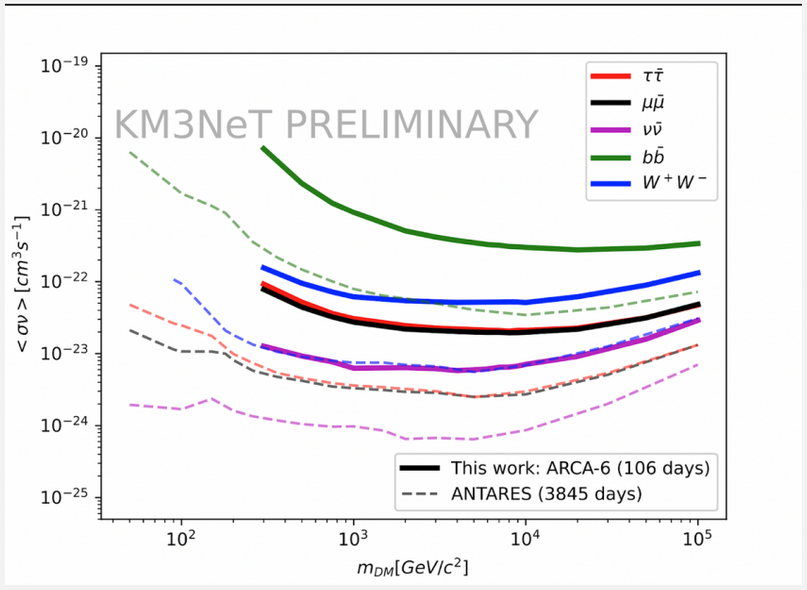
α	N^{cat}	$N^{\mathrm{sim}}(QF = 0.9)$	$N^{\mathrm{sim}}(QF = 0.8)$	$N^{\mathrm{sim}}(QF = 0.5)$
0.01	7408	4641	8111	10003
0.05	6692	2745	5790	9532
0.10	6549	1855	4063	8684

Dark matter indirect searches with neutrinos: from the galactic center, the Sun...

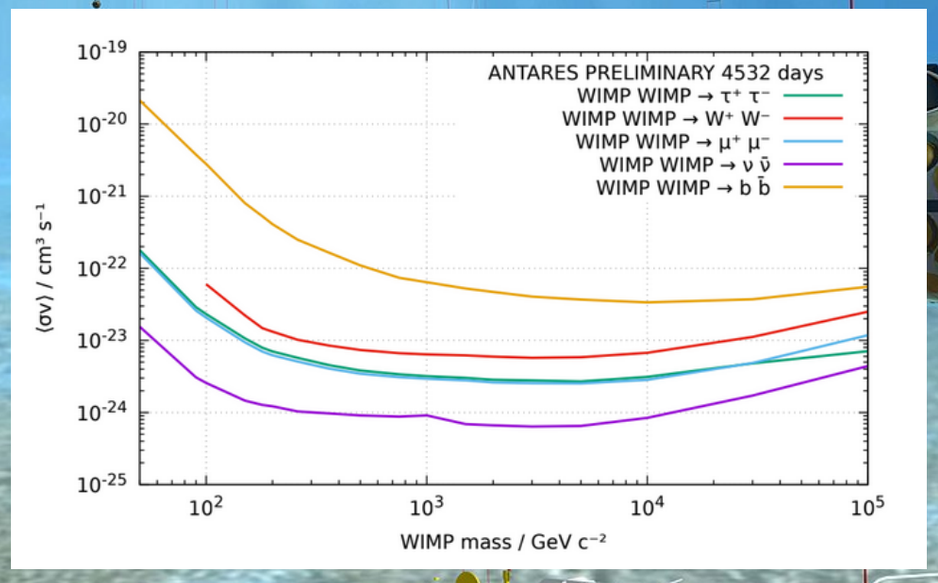
Physics beyond the Standard Model expectations: dark matter

ANTARES and first KM3NeT data investigated looking for indirect dark matter signatures

First KM3NeT data (8 and 21 lines) [PoS(ICRC2023)1377]



Final ANTARES data set unblinded - test statistics is consistent with background hypothesis [PoS(ICRC2023)1375]



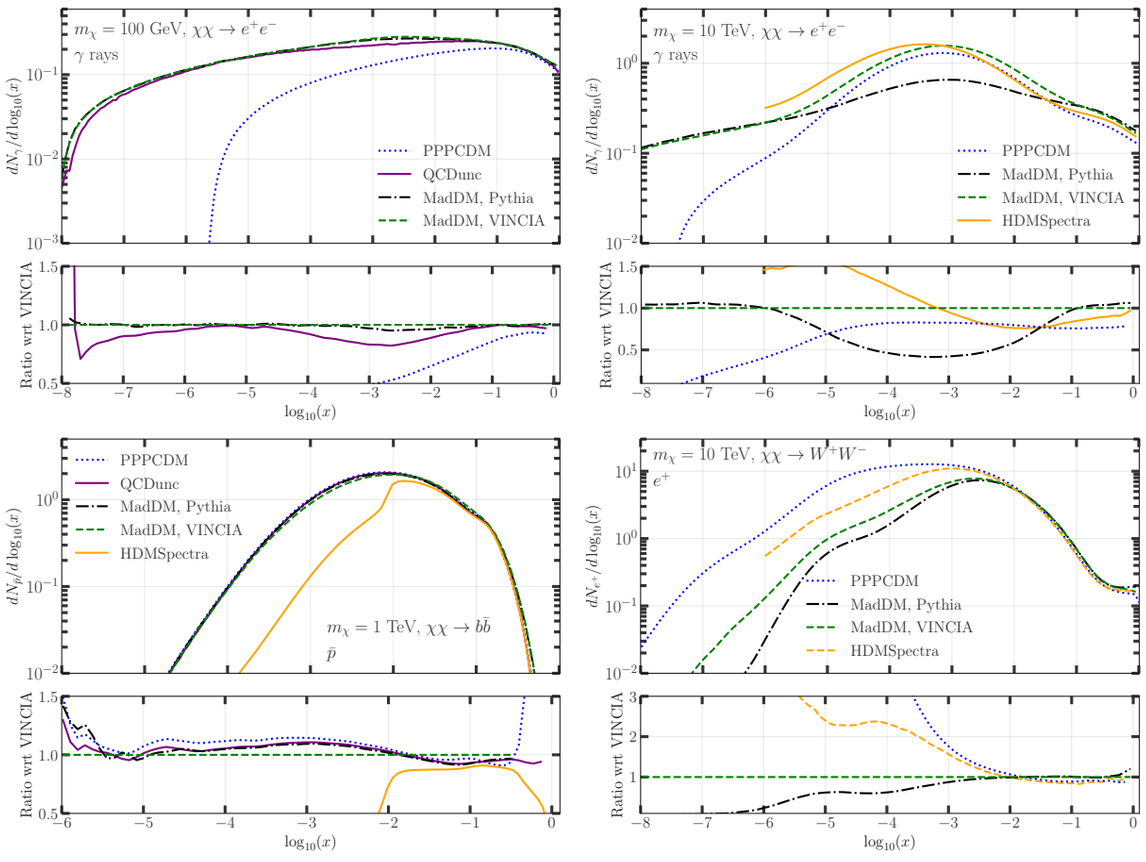
Also: combined search for dark matter joining neutrinos and γ rays ongoing

Cosmic messenger spectra for indirect dark matter searches

Novelties with respect to PPPCDM (standard in the community)

- Polarisation effects taken into account during the whole shower evolution.
- All the helicity information of the produced particles in DM annihilation/decay during the whole process. Therefore, EW corrections are properly taken in account where all the possible EW branchings are included (even those involving triple-gauge couplings).
- EW corrections are properly resummed through Sudakov factors.
- Decays of heavy resonances are interleaved with the rest of the shower evolution.
- Off-shell effects are taken into account for the annihilation channels: WW/ZZ/HZ. For this case, we produce the spectra for the four-body channels, e.g. DM DM -> WW -> 4f. Therefore spanning masses from 5 GeV to about the mass of the gauge boson.
- Spectra for two new channels (never considered before): HZ and gamma Z.
- Full loop effects for loop-induced annihilation channels: gamma gamma, gamma Z and gluon gluon.
- 5M annihilation events for each channel and each DM mass (reducing statistical uncertainties in the tails below 5%).
- The spectra calculated for DM masses between 5 GeV and 100 TeV.

Our results: MadDM + VINCIA



Large differences in spectra like gamma rays!

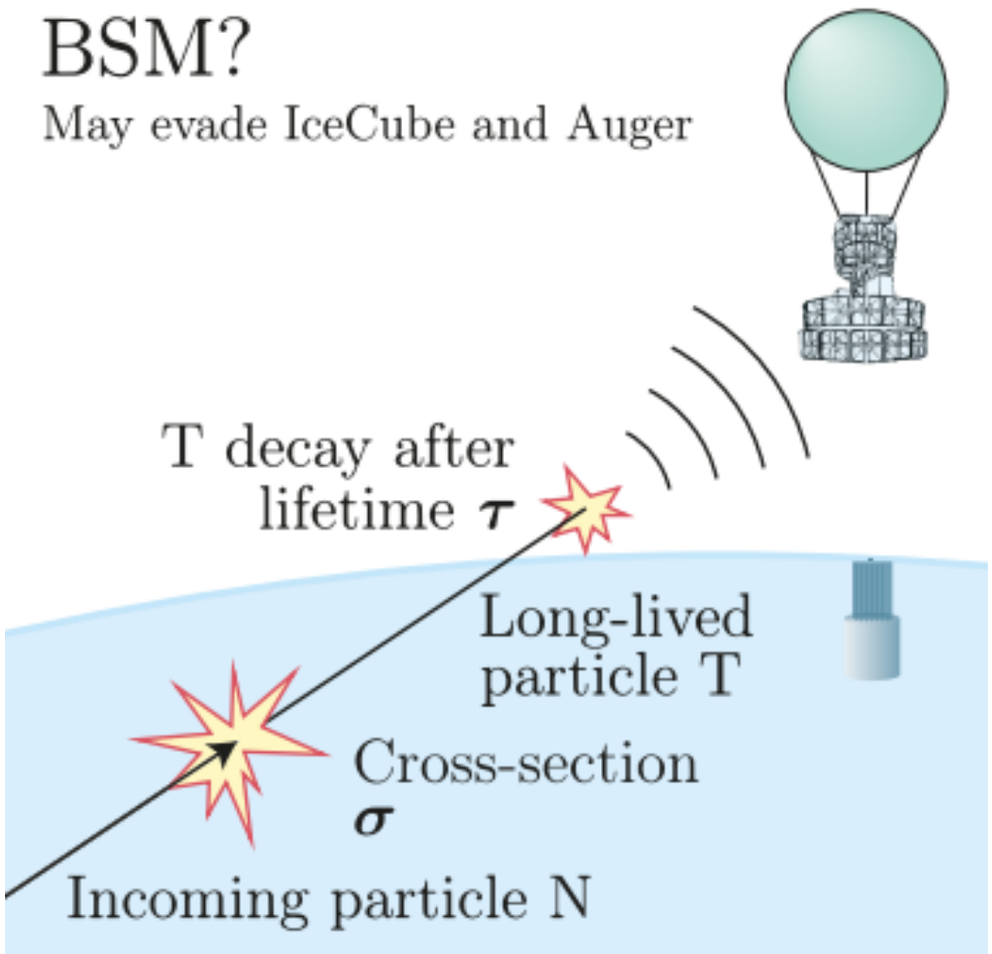
Tables available on https://github.com/ajueid/CosmiXs

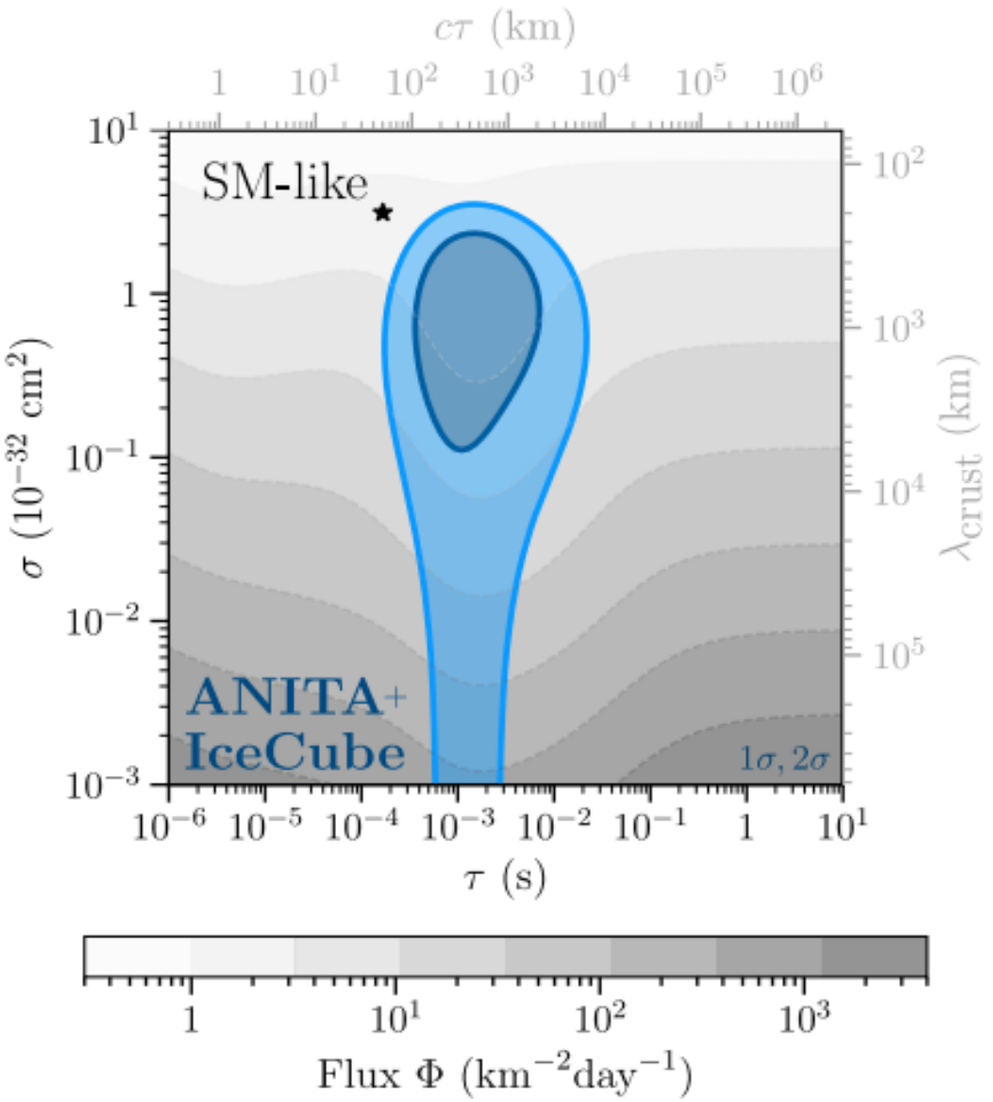
C. Arina, M. Di Mauro, N. Fornengo, J. Heisig, A. Jueid and R. Ruiz de Austri, arXiv:2312.01153

Ultra high-energy anomalous events: BSM?

JHEP 07 (2023), 005. arXiv:2305.03746
T. Bertolez-Martinez, C. Arguelles, I. Esteban, J. Lopez-Pavon, I. Martinez-Soler, J.Salvado.

ANITA-IV recently announced detection of new, unsettling UHE events. Their internal consistency and the implications of the lack of similar events in IceCube in SM-like and BSM scenarios is studied.





The analysis highlights the importance of simultaneous observations by high-energy optical neutrino telescopes and new UHE radio detectors to uncover cosmogenic neutrinos or discover new physics.

L4: Baryogenesis, dark matter and cosmic messengers

A bit of a hodgepodge of astro-particle related topics

A lot of activity at IFIC,

both from theory and experimental sides

FELIZ AÑO NUEVO

2024