The Dark Universe
A Synergic Multimessenger Approach

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Dark matter evidence has grown to become one of the pillars of modern cosmology. However, we are still lacking a fundamental understanding of its origin and nature. The hypothesis that DM is composed by a new particle has profound implications for our understanding of fundamental physics, but up to now DM evidences are of purely gravitational origin and no unambiguous proof that DM is composed by particles has been provided.

The goal of this project is to test the particle physics interpretation of DM by establishing a comprehensive approach to the whole host of cosmic messengers: electromagnetic radiation at any relevant frequency (radio, infrared, X rays, gamma rays), neutrinos, charged cosmic rays and gravitational waves.

This will be complemented be the development of two innovative techniques specifically conceived to extract the faint DM signals from the overwhelming astrophysical backgrounds: statistical cross-correlations between gravitational tracers (weak lensing, large scale structure observed through galaxies and galaxy-clusters catalogs) and electromagnetic signals emitted from DM, thus combining together the two key manifestations of DM as an elementary particle; exploration of the ability of Machine Learning techniques to identify a DM signal.

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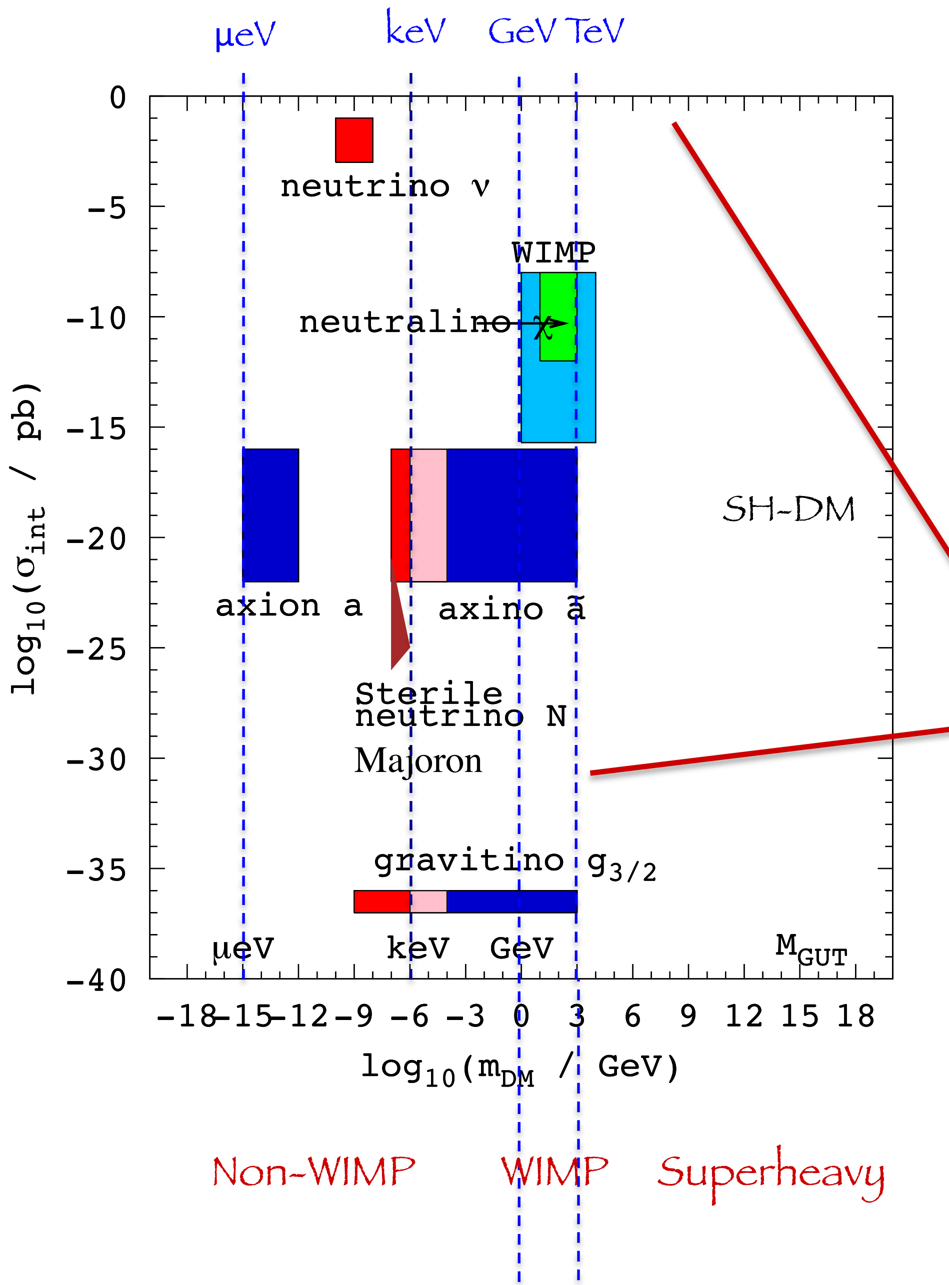
	Fabrizio Nesti	BSM
	Luigi Pilo	GW, Gravity
	+	Postdoc

If DM is a new particle ...



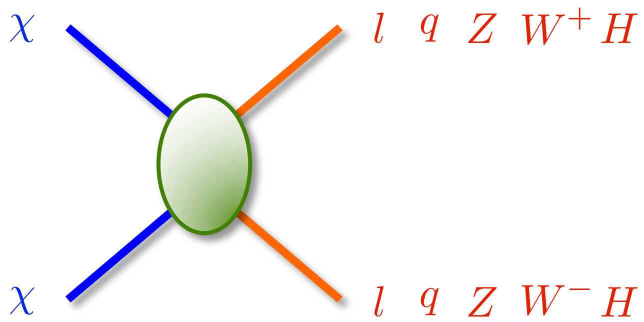
"Strong (-ish)"
- Self-interacting
- Technicolor DM
- ...

"EM (-ish)"
- Millicharged DM
- Electric/magnetic dipole
- ...

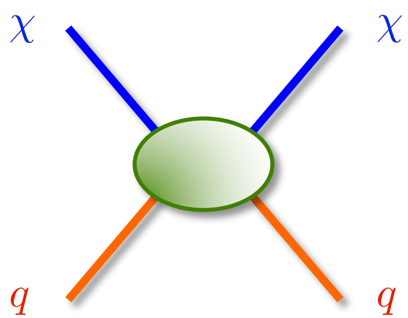
Weak
- WIMP

Gravitational
- Particle
- PBH

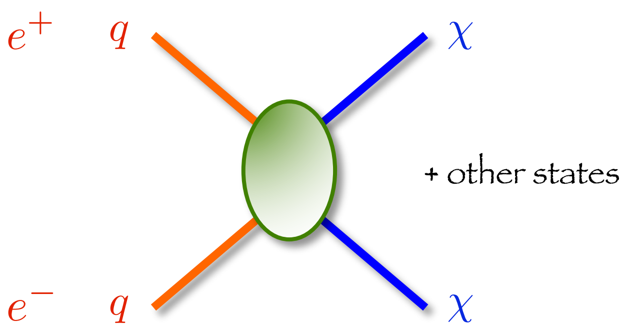
… It can do something



Annihilation (or decay)



Scattering with ordinary matter

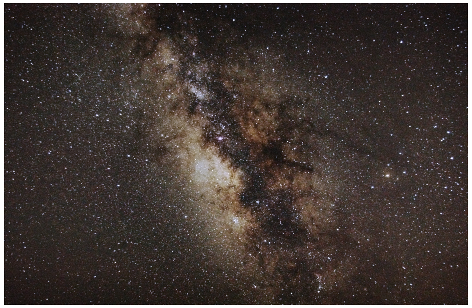


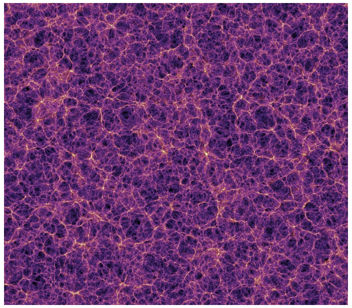
Production at accelerators

Where to search for a signal ...

We can exploit every structure where DM is present ...

- Our Galaxy
  - Smooth component
  - Subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - Smooth component
  - Individual galaxies
  - Galaxies subhalos
- "Cosmic web"





... and what

...and we have a large number of messengers at disposal

- Our Galaxy
  - Smooth component
  - Subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - Smooth component
  - Individual galaxies
  - Galaxies subhalos
- "Cosmic web"

A

Charged CR ($e^{\pm}$, antip, antiD) [G]

Neutrinos [G,E]

Photons [G,E]

- Gamma-rays
  - Prompt production
  - IC from $e^{\pm}$ on ISRF and CMB
- X-rays
  - IC from $e^{\pm}$ on ISRF and CMB
- Radio
  - Synchro from $e^{\pm}$ on mag. field

B

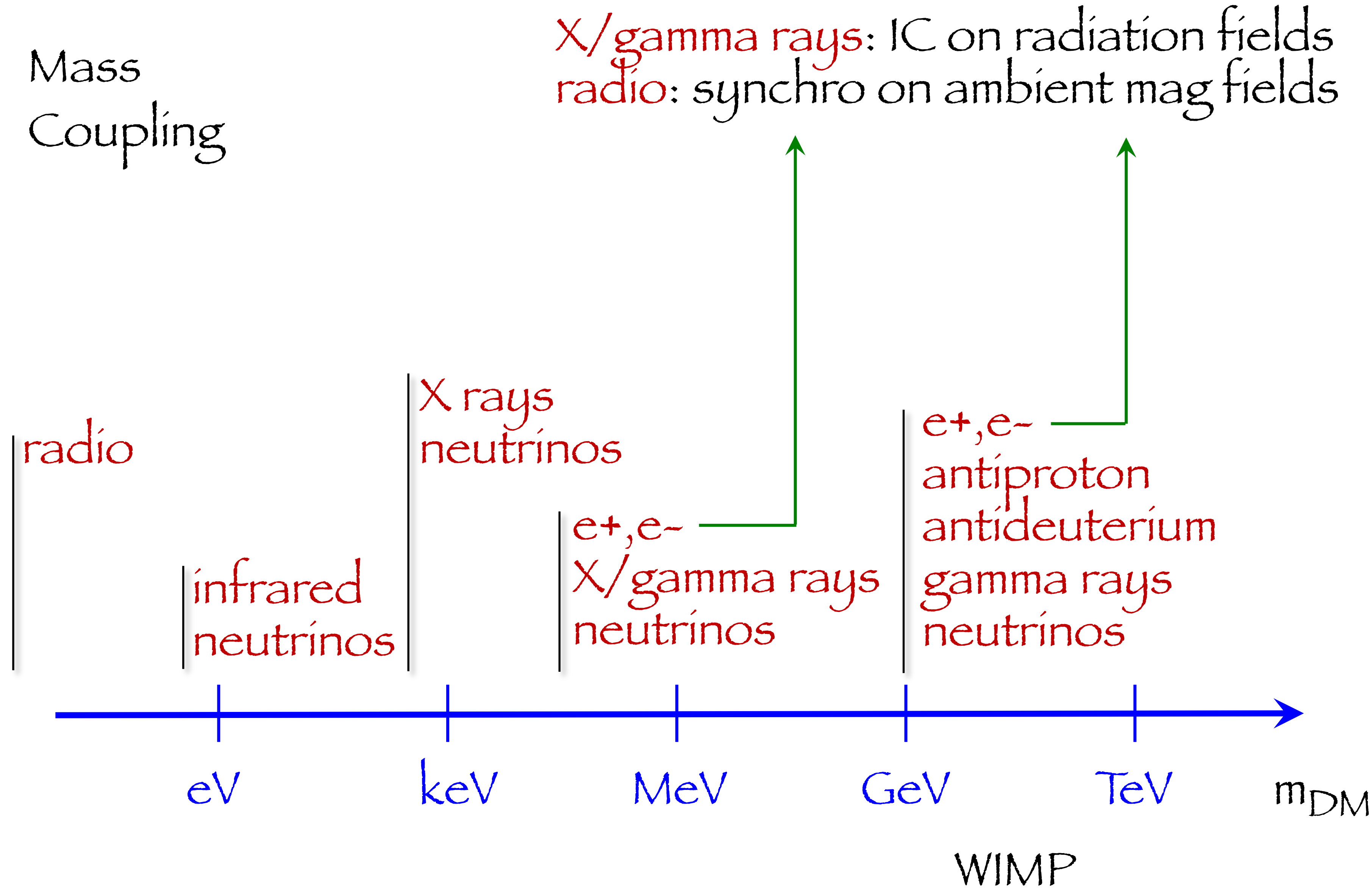
Direct detection [L]

A: $\mathrm{DM} + \mathrm{DM} \longrightarrow (\ldots) \longrightarrow \mathrm{signal}$

B: $\mathrm{DM} + \mathcal{N} \longrightarrow \mathrm{DM} + \mathcal{N}$

Local [L] - Galactic [G] - Extragalactic [E]

The Multimessenger Landscape



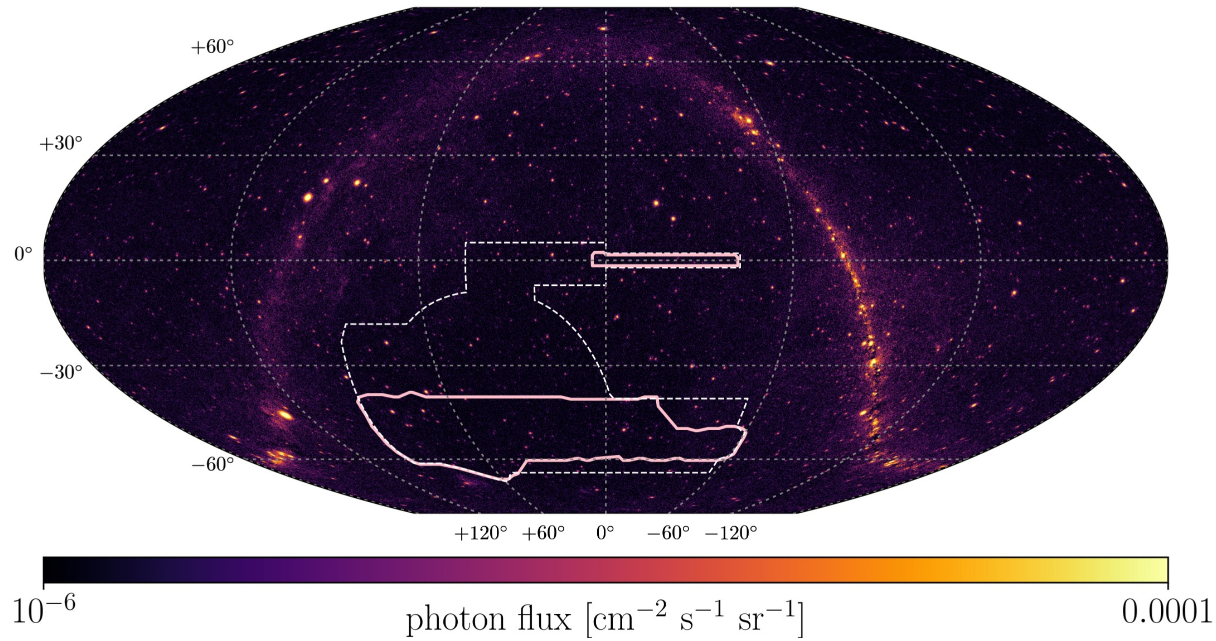
Many arrows in our quiver

However ...

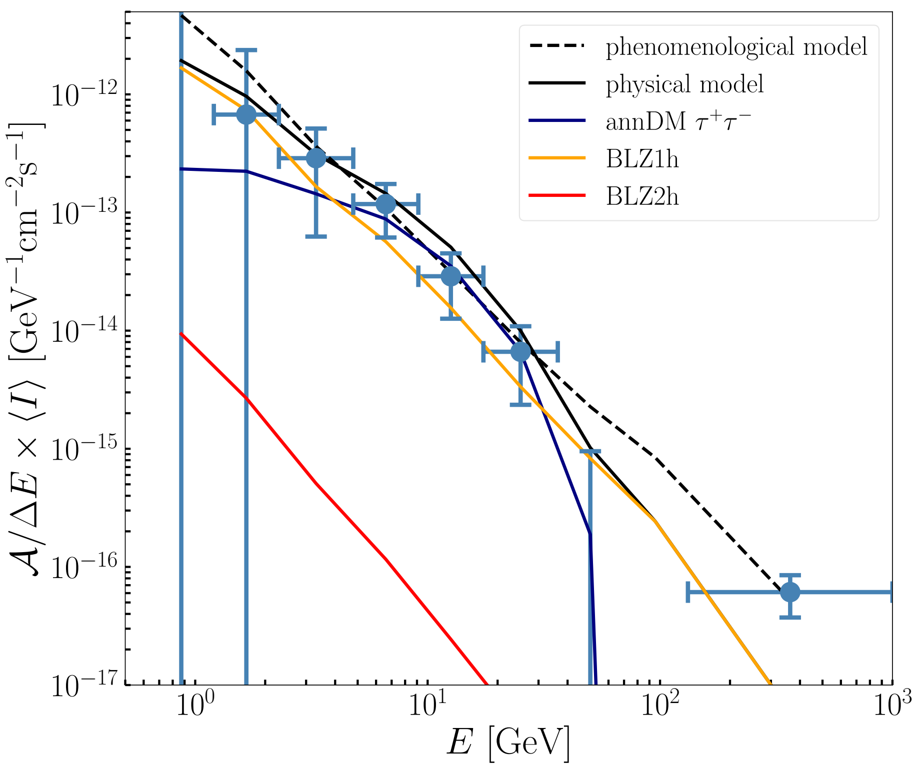
DM signals are faint!

And there are astrophysicsl backgrounds, too

WP1	Multimessenger Signals for DM and its Astrophysical Backgrounds	
1a	Radio, Infrared, X rays, Gamma Rays	Ullio, Taoso
1b	Neutrinos	Petkov
1c	Charged Cosmic Rays	Donato
1d	Gravitational Waves	Berejiani
1e	Direct Detection	D'Eramo
WP2	DM Distribution at Any Scale and its Impact on Multimessenger Signals	
2a	Small Scales: Galaxies, Dwarfs, Subhalos, Compact Objects	Salucci
2b	Large Scales: Clusters, Cosmic Web	Pietroni
WP3	DM Particle Candidates and Connection to Multimessenger Signals	
3a	The Light DM Window: Axions, ALP	D'Eramo/RU3
3b	Sterile Neutrinos and the keV window	Giunti/RU1
3c	The MeV-GeV-TeV Scales and Beyond	Masiero, De Simone
3d	Portals, hidden sectors, self-interacting, dissipative DM	Berejiani
WP4	Cross Correlations of Multimessenger Signals	Fornengo
WP5	Artificial Intelligence Methods for Astroparticle Physics	
5a	Machine Learning for DM Multimessenger Searches	Fornengo
5b	Machine Learning for DM Particle Physics Searches	De Simone



DES x Fermi



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WP1
Multimessenger Signals for DM and its Astrophysical Backgrounds

A. Detailed models of CR-induced emission and tuning with data. Delivery of detailed emission maps.

B. Test of CR transport models with gamma-ray data.

C. Test of CR lepton components via inverse Compton and synchrotron emissivity, jointly using radio, microwave (including polarization) and gamma-ray data to disentangle different classes of sources.

D. Impact of the above analyses on DM searches. Infer at which level a subdominant emission like DM can be distinguished from the foregrounds.

E. Study of the antiproton and antideuteron components, in view of AMS data and in preparation of the GAPS mission.

F. Test of light DM (ALPs, dark photons, sterile neutrinos) with radio, infrared and X-ray emissions.

G. Investigation of DM-enhanced compact objects and derivation of GW waveforms from their coalescence. Set up of analysis protocols for LIGO/Virgo, derivation of bounds on DM.

WP2
DM Distribution at Any Scale and its Impact on the Multimessenger Signals

A. Dynamical models for the inner part of galaxies and test on astrophysical data.

B. Implementation of techniques to derive mass profiles of dwarf galaxies.

C. Development of perturbation theory techniques to improve predictions of statistical N-point correlators. Calibration on cosmological observations. Extension to the non-linear regime.

D. Identification of crucial elements which differentiate CDM from other types of DM when applied to cross-correlations.

WP3
DM Particle Candidates and Connection to Multimessenger Signals

A. Definition of DM effective models in hidden sectors, study of their cosmology including modified DM clustering, interplay between direct and indirect DM searches.

B. ALP cosmology and its contribution to DM and dark radiation, relevance for future CMB surveys.

C. Systematic investigation of portals and its model realizations for direct and indirect DM signals.

D. Systematic investigation of sterile neutrinos and connection to the origin of neutrino masses.

E. Development of effective theories for sub-GeV DM, study of their direct detection rate and rigorous predictions of its multiwavelength emission. Identification of the discovery potential of future satellite experiments and definition the scope of their missions.

F. Elaboration of a novel class of models with inelastic DM processes and derivation of their DM signatures in multiwavelength emission.

G. Embedding of effective models in well-behaved New Physics models.

WP4
Cross Correlations of Multimessenger Signals

A. First measurement of the cross-correlation between gamma-rays (Fermi-LAT) and DES cosmic shear (first year of data, Y1). Preparation and delivery of the analysis for DES Y3.

B. Update to the final Fermi-LAT statistics of the measurement and theoretical interpretation of the cross-correlation between gamma rays and: galaxy catalogs, clusters catalogs.

C. Investigation of the cross-correlation for next-generation gamma-rays detectors (e-Astrogam for low energies, CTA for high energies).

D. Extension of the cross-correlation technique to radio emission. Bounds on both light and heavy DM particles. Forecasts and preparation for SKA1.

E. Study for the extension of the cross-correlation technique to X-rays for bounds on ALP, dark photons and sterile neutrinos. Study of the potentialities for e-ROSITA.

F. First theoretical predictions for the cross-correlations with HI intensity mapping and preparation for SKA1 and precursors.

G. Investigation of higher-order statistics (three-point cross-correlations).

H. Preparation of the multi-wavelength cross-correlation analysis for the Euclid mission.

WP5
Artificial Intelligence Methods for Astroparticle Physics

A. Supervised learning trained on theoretical modeling of the expected DM signals and their astrophysical backgrounds, including adversarial network techniques.

B. Unsupervised learning to extract hidden features in the multi-wavelength maps.

C. Deep learning applied to the cross-correlation observables.

D. Predictive modeling and neural networks for the exploration of high-dimensional parameter spaces of DM particle physics models.

Main International Collaborations

Torino	Amsterdam, Aachen, Leiden, Stanford, Richmond, Virginia Tech, Beijing, Paris LPTHE
Padova	CERN, DESY, Amsterdam, Imperial College, KIPMU, Stockholm, Geneva
SISSA	Amsterdam, NIKHEF, CERN, IFT Madrid, Nottingham, LANL, Berkeley, Santa Cruz
L'Aquila	Moscow, Munich, Minnesota, Novosibirsk, ORNL, Sydney, Tennessee
INFN	Madrid, Valencia, Paris Saclay, Paris LPTHE, Tokyo, Minnesota, Beijing, Moscow, Geneva, IHES Paris