Discovery of new optical and X-ray supernova remnants in nearby galaxies: Improved identification through multi-line diagnostics

Maria Kopsacheili [1], [2]

[1]Instituto de Ciencias del Espacio, Barcelona Spain [2]Institut d'Estudis Espacials de Catalunya - IEEC

Goal: Systematic, multi-wavelength Study of Supernova Remnants (SNRs)

- Detection and characterization of SNR populations in different galactic environments
- Investigation of correlations between galactic and SNR properties
- Quantification of feedback processes from SNRs to the interstellar medium (ISM)

Optical identification of supernova remnants

- Empirical diagnostic [S II]/Hα > 0.4 (e.g. Dodorico et al. 1980)
  → Few dozens of SNRs/galaxy
- Model based diagnostics using MAPPINGS III (Kopsacheili et al. 2020)
  → SNRs: Shock models (Allen et al. 2008)
  → H II regions: Photoionization models (Kewley et al. 2001; Levesque et al. 2010)
  → Emission line ratios: $\frac{[\mathrm{S\,II}]}{\mathrm{H}\alpha}, \frac{[\mathrm{N\,II}]}{\mathrm{H}\alpha}, \frac{[\mathrm{O\,I}]}{\mathrm{H}\alpha}, \frac{[\mathrm{O\,II}]}{\mathrm{H}\beta}, \frac{[\mathrm{O\,III}]}{\mathrm{H}\beta}$ (combination in 2 and 3 dimensions) → Multi-line diagnostics using Support Vector Machine

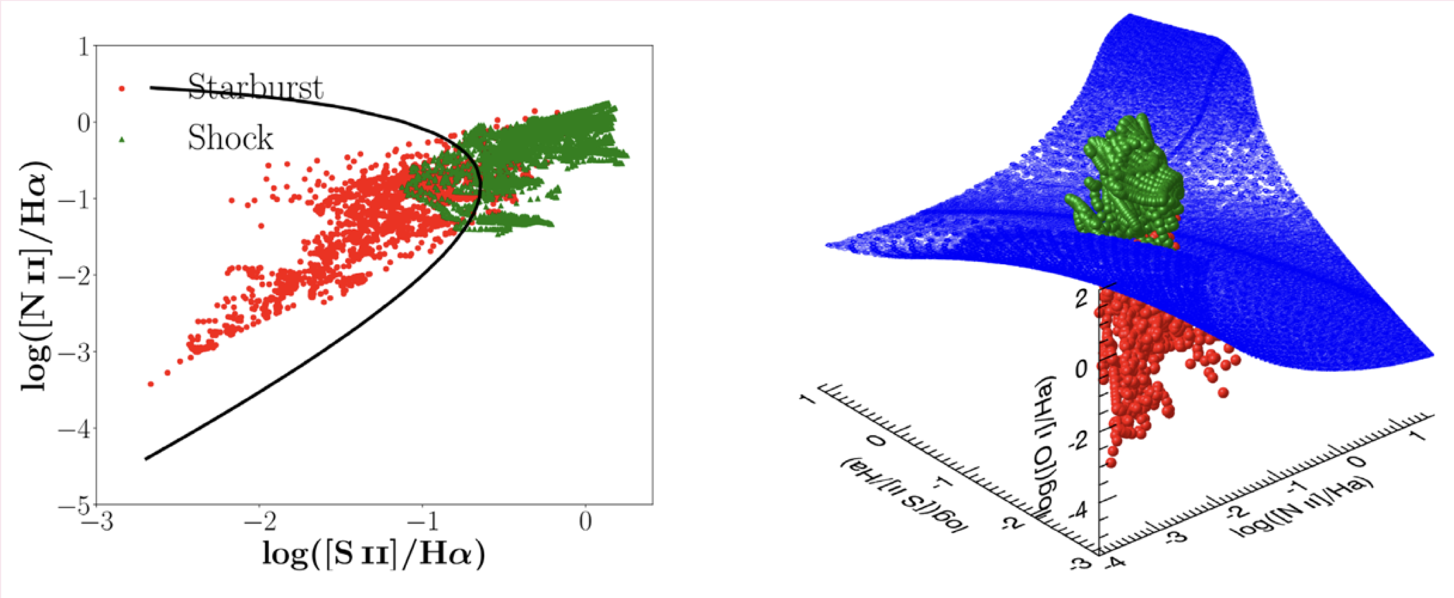

Figure 1. Example of the multi-line diagnostics. A 2D diagnostic (left) and a 3D diagnostic (right). Red and green points correspond to photoionzation and shock models, respectively. All the diagnostics can be found in Kopsacheili et al. (2020) and in this GitHub repository.

New supernova remnants

The multi-line diagnostics from (Kopsacheili et al., 2020) were applied to the MUSE IFU data of the galaxies NGC 7793, NGC 628, and NGC 5068, for the optical identification of SNRs.

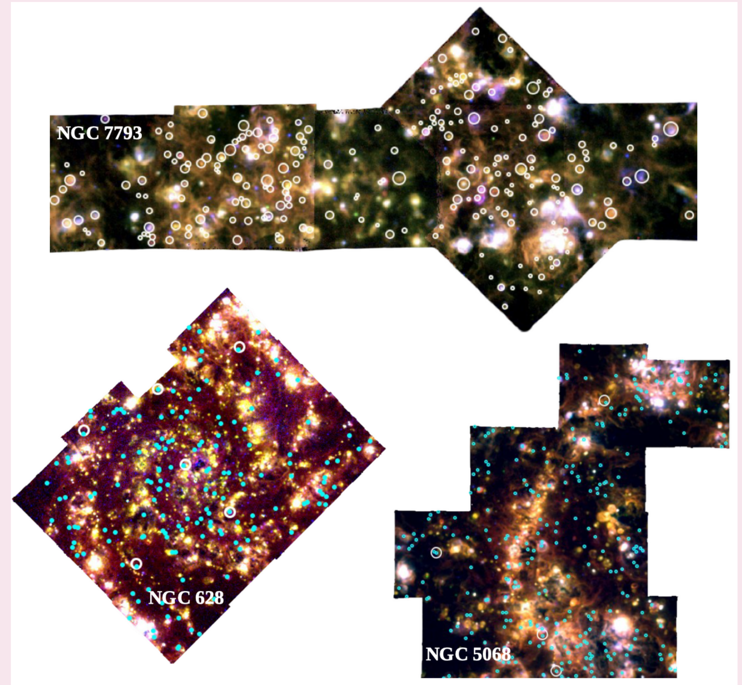

Figure 2. The new, optical supernova remnants in the galaxies NGC 628, NGC 5068, and NGC 7793.

Luminosity Functions

- 1-dimensional luminosity function (LF) of Hα, [S II](6717,6731ÅÅ), [N II](6584Å), [O III](5007Å) for the three galaxies
- 2-dimensional LF of Hα-[S II], Hα-[N II], [S II]-[N II], [S II]-[O III], [N II]-[O III] for NGC 7793.

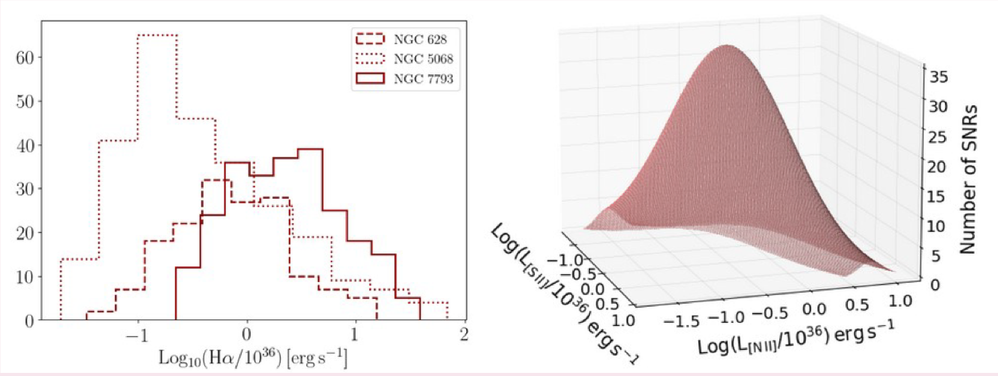

Figure 3. *Left:* The Hα luminosity functions of SNRs in the galaxies NGC 628, NGC 5068, NGC 7793. *Right:* The joint luminosity function [N II]-[S II] of SNRs in NGC 7793.

The results related to NGC 7793 are presented in Kopsacheili et al. (2024). For the other galaxies, the study is under preparation by Musté et al.

Properties of optical supernova remnants

Shock velocities

We used shock models from MAPPINGS III and MAPPINGS V to estimate shock velocities. Most SNRs exhibit velocities below 300 $\mathrm{km\,s^{-1}}$, consistent with typical values for optically selected SNRs.

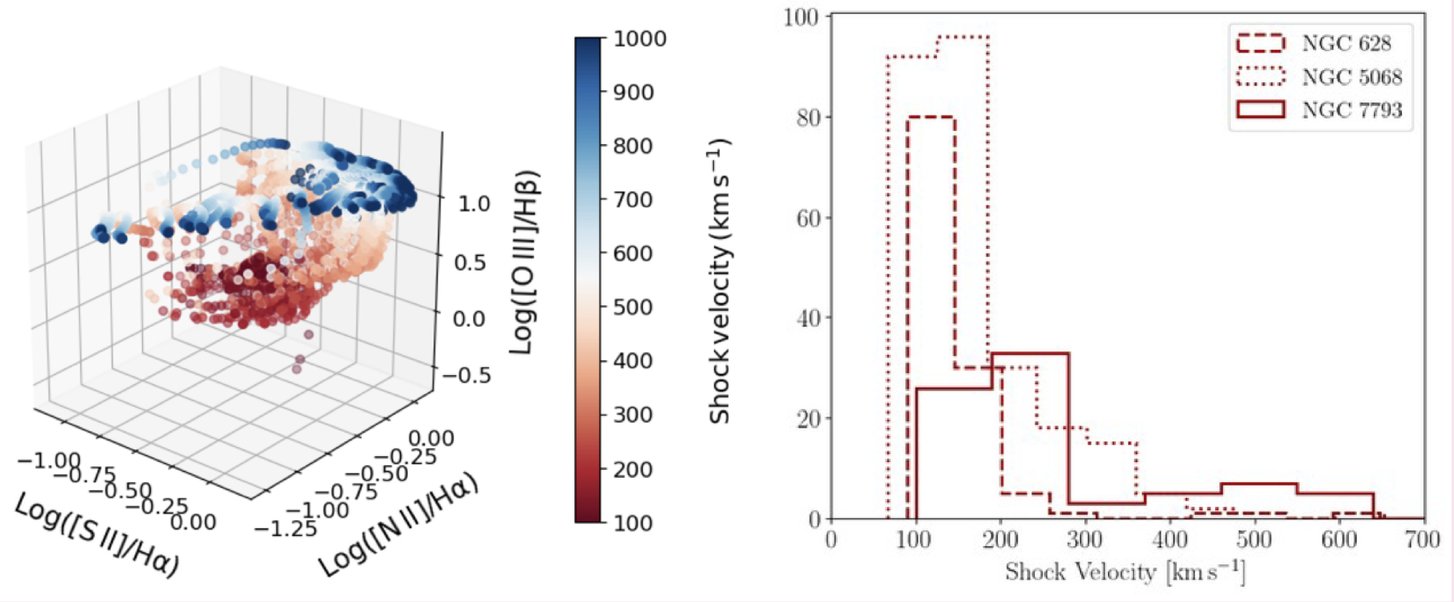

Figure 4. *Left:* Shock models from MAPPINGS III in the 4D-space $\frac{[\mathrm{S\,II}]}{\mathrm{H}\alpha} - \frac{[\mathrm{N\,II}]}{\mathrm{H}\alpha} - \frac{[\mathrm{O\,III}]}{\mathrm{H}\beta}$ − shock velocity. We used the observed emission-line ratios and interpolate in the shock-model space to obtain the SNR shock velocity. *Right:* The shock velocity distribution of SNRs in the galaxies NGC 7793, NGC 628, and NGC 5068. For the two latter we have used the shock models of MAPPINGS V.

Density

For the estimation of the electron density, we have used the relation between density and the emission-line ratio of [S II] lines (e.g. Osterbrock and Ferland 2006). For this, we have assumed four different temperatures, typical in optical SNRs.

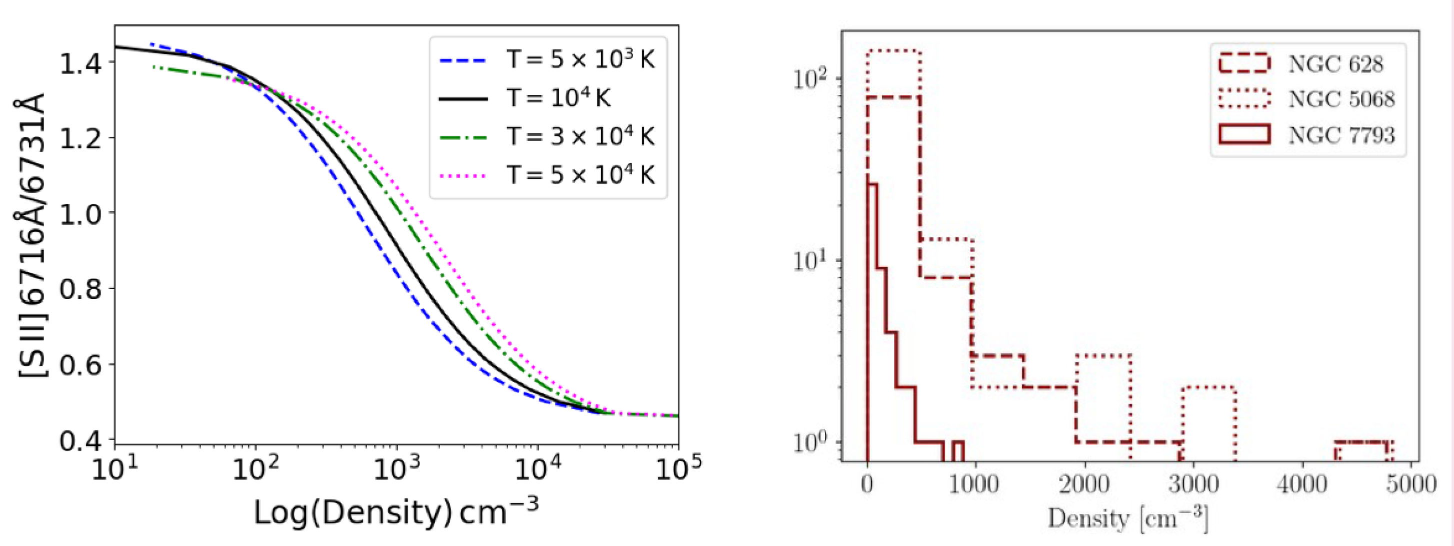

Figure 5. *Left:* The theoretical relation between eletron density and the emission line ratio of [S II] lines for 4 different temperatures. *Right:* The distribution of post-shock densities of the SNRs in the three galaxies, assuming a temperature of 10^4 K.

Identification of X-ray supernova remnants

With a new, larger sample of optical SNRs, we searched for X-ray counterparts using archival *Chandra* data. We identified a total of 12 X-ray counterparts, 11 of which are newly reported. For NGC 7793, we present a more detailed analysis, while the data for NGC 628 and NGC 5068 are still under investigation.

Galaxy	New opt. SNRs	X-ray SNRs	References
NGC 7793	∼ 200	5	Kopsacheili et al. (2025)
NGC 628	∼ 79	3	Musté et al. (in prep.)
NGC 5068	∼ 176	4	Musté et al. (in prep.)

Table 1. New optical and X-ray SNRs.

At such distances, it is challenging to extract spectra for SNRs in order to estimate their physical properties. As an alternative, we calculate the hardness ratios of the sources, using the following energy bands: soft (S) = 0.5–1.2 keV, medium (M) = 1.2–2.0 keV, and hard (H) = 2.0–7.0 keV.

Color-color diagrams

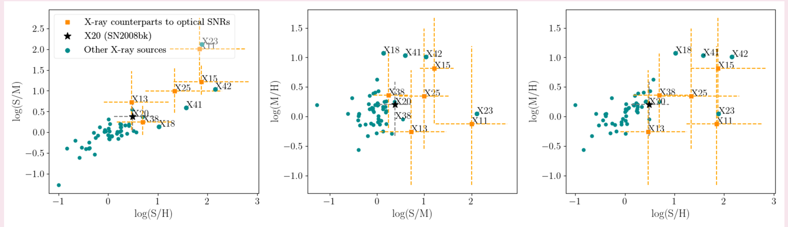

Figure 6. Hardness ratios of the X-ray sources in NGC 7793. The orange squares are those that coincide with optical SNRs, and as expected, they occupy the softer part of the diagrams.

Spectra and properties of X-ray supernova remnants in NGC 7793

Spectra

We also detected two of the X-ray SNRs in NGC 7793 in *XMM-Newton* data and extracted their spectra, shown in fig. 7. Both spectra are well fitted by thermal models and exhibit prominent emission lines, including O VII, O VIII, and Ne IX.

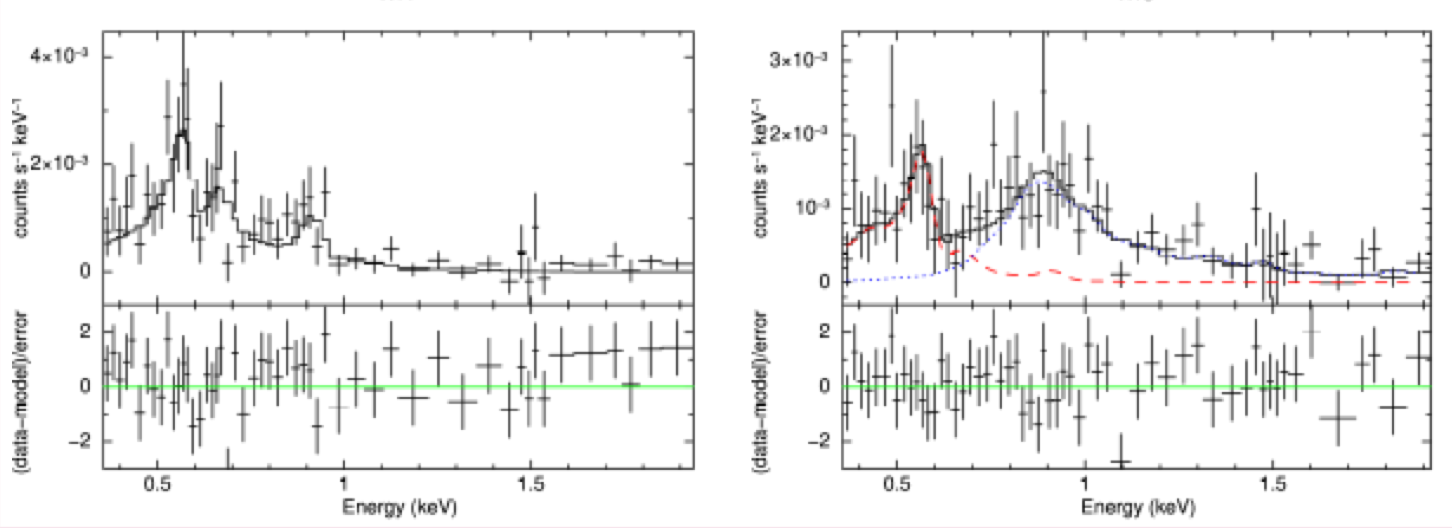

Figure 7. Spectra of two X-ray SNRs in NGC 7793. The spectrum on the left is best fitted by a single thermal component at kT = 0.13 keV, while the spectrum on the right required two thermal plasma components: a soft component with kT < 0.12 keV and a harder component at kT = 0.78 keV

Correlation with optical properties

We investigated potential correlations between the X-ray and optical properties of SNRs. Our first finding is that all X-ray-detected SNRs exhibit strong [O III] emission, consistent with relatively high shock velocities. We also observed a positive correlation between electron density – estimated from the [S II] line ratio – and both the X-ray luminosity and the hardness ratio $\log_{10}(S/H)$, as shown in fig. 8. However, the sample size is very limited, and despite the physical plausibility of this trend, there is up to a 40% probability that it arises by chance. Larger samples are required to confirm this correlation.

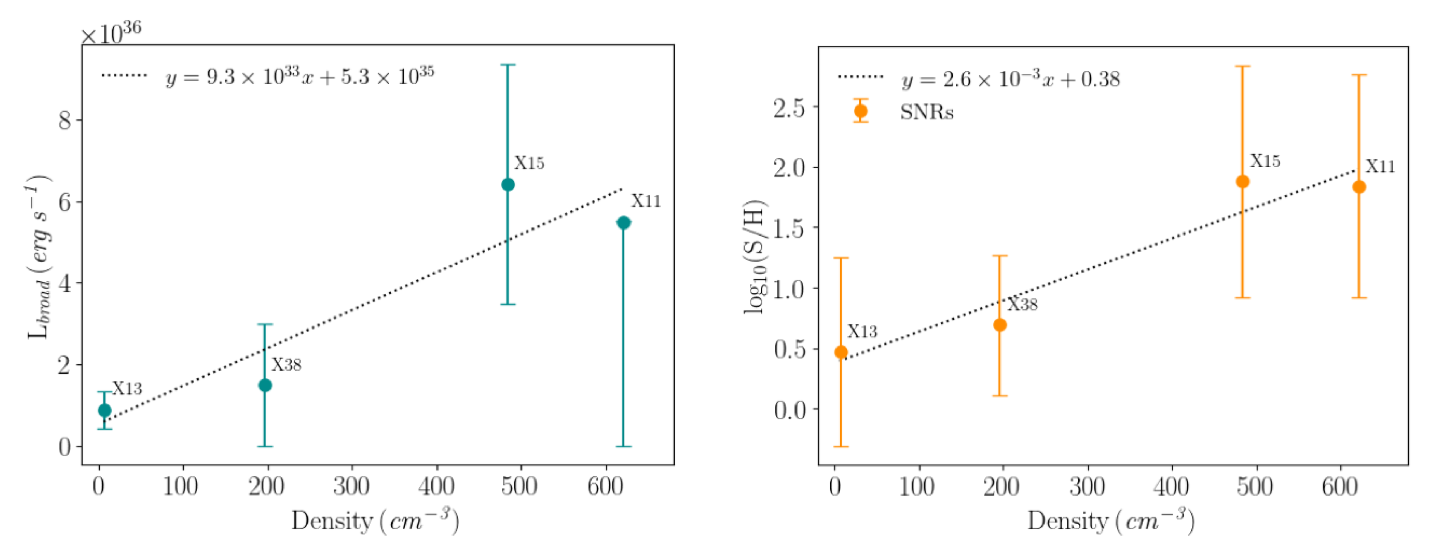

Figure 8. *Left:* The X-ray luminosity in the broad band (0.5-7 keV), of four X-ray SNRs in NGC 7793, as a function of their density, calculated using the [S II]6717/31 emission line ratio. *Right:* The $\log_{10}(S/H)$ color of the same sources, as a function of the density. In both cases the best-fit line is also shown

Finally, in this work we also report two candidate X-ray SNRs – one of which shows a spectrum similar to those in fig. 7 – as well as the identification of the X-ray counterpart to supernova 2008bk (Kopsacheili et al. 2025).

Future goals

In the future, we plan to extend this analysis to additional galaxies with available MUSE and *Chandra* data, and to incorporate observations at other wavelengths, such as infrared and radio.

References

Mark G. Allen, Brent A. Groves, Michael A. Dopita, Ralph S. Sutherland, and Lisa J. Kewley. *ApJS*, 178:20, 2008.
S. Dodorico, M. A. Dopita, and P. Benvenuti. *A&AS*, 40:67, 1980.
L. J. Kewley, M. A. Dopita, R. S. Sutherland, C. A. Heisler, and J. Trevena. *ApJ*, 556:121, 2001.
M. Kopsacheili, A. Zezas, and I. Leonidaki. *MNRAS*, 491:889, 2020.
Maria Kopsacheili, Cristina Jiménez-Palau, Lluís Galbany, Panayotis Boumis, and Raúl González-Díaz. *MNRAS*, 530:1078, 2024.
Maria Kopsacheili, Konstantina Anastasopoulou, Nanda Rea, Claudia Patricia Gutiérrez, and Lluis Galbany. *arXiv e-prints*, page arXiv:2506.09120, 2025.
Emily M. Levesque, Lisa J. Kewley, and Kirsten L. Larson. *AJ*, 139:712, 2010.
Donald E. Osterbrock and Gary J. Ferland. *Astrophysics of gaseous nebulae and active galactic nuclei*. 2006.

Acknowledgments: I acknowledge financial support from MICINN (Spain) through the Juan de la Cierva-Incorporación programme [JC2022-049447-I] and the Unidad de Excelencia María de Maeztu [CEX2020-001058-M]. I also thank all collaborators involved in the presented projects, especially Dr. K. Anastasopoulou, Dr. N. Rea, Ms. C. Jiménez-Palau, Dr. Panayotis Boumis, Dr. I. Leonidaki, and Prof. A. Zezas, for their active contributions to the studies shown in this poster.