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Ministero dell'Università e della Ricerca
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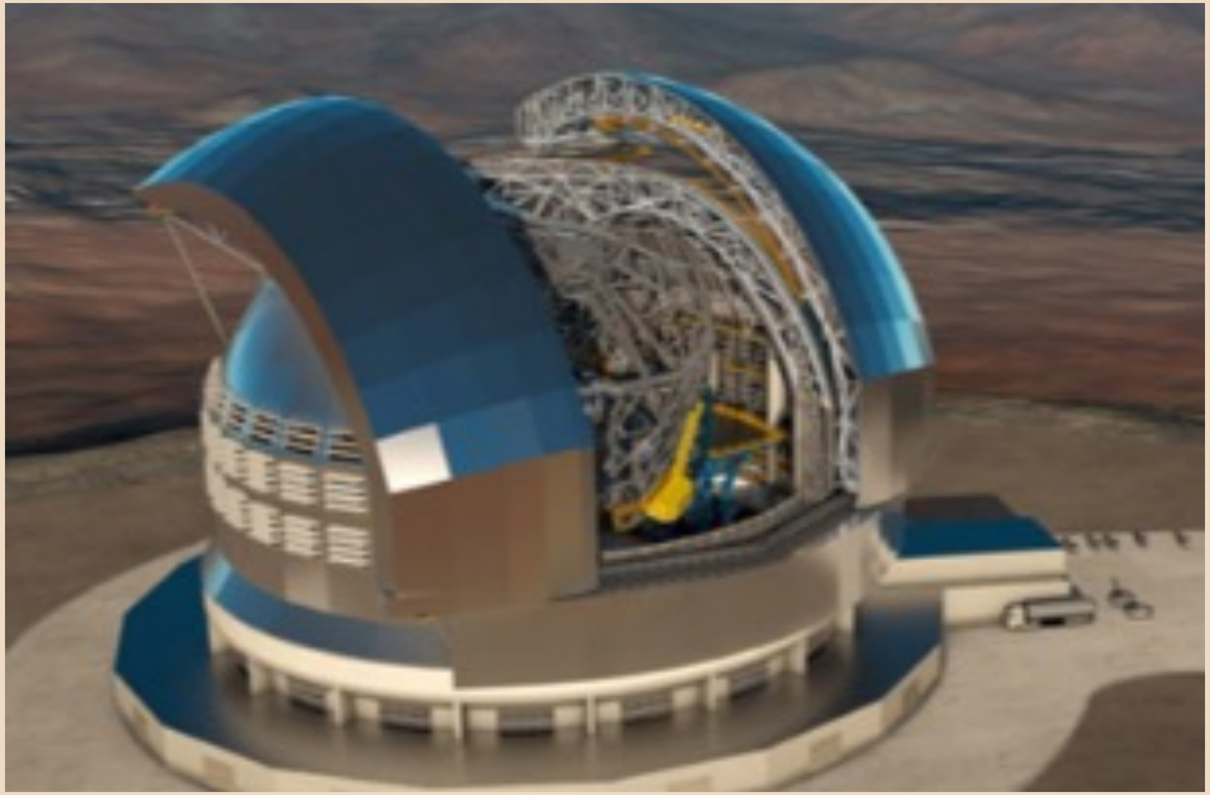
INAF ISTITUTO NAZIONALE DI ASTROFISICA

STILES

Characterization of exoplanetary atmospheres



INAF OAPA
&
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Quantum Reservoir Computing and Quantum Extreme Learning Machines

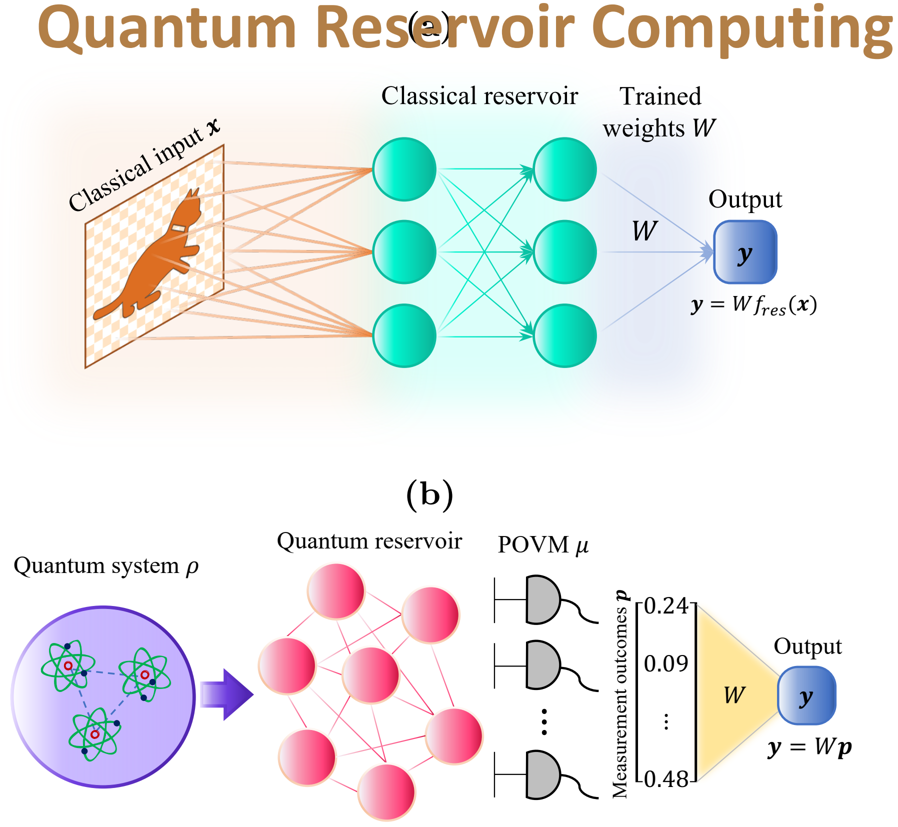
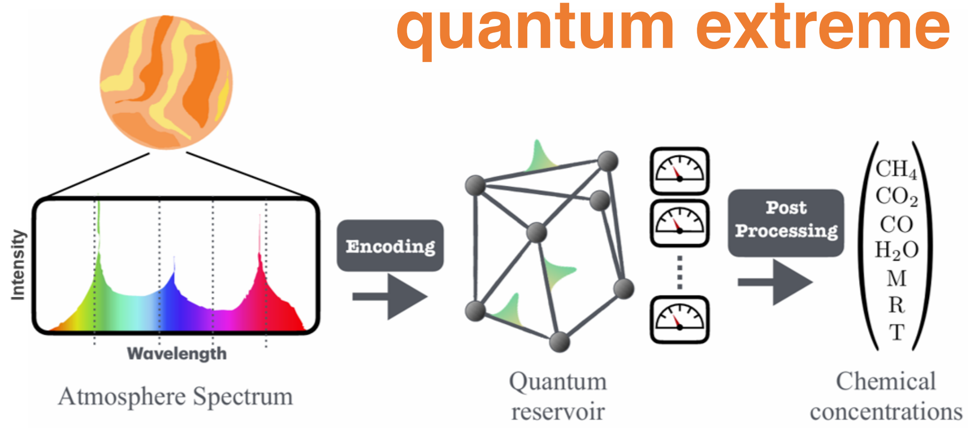
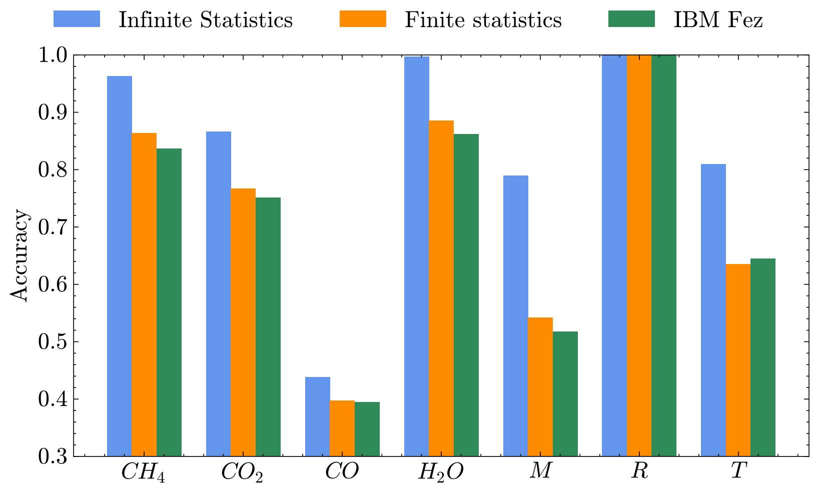


Figure 1. Schemes of principle of **(a)**: Classical ELM setup; **(b)**: QELM setup for classical information processing.

- Reservoir computing is a simpler version of NN in which the input signal is connected to a fixed and random dynamical system (the reservoir), creating a higher dimension embedding.
- This embedding is connected to the desired output via trainable links (weights).
- the weights between the input and the ‘reservoir’ and also the weights of the ‘reservoir are randomly assigned and not trainable
- the weights between the reservoir and the output layer are trainable and can be learned
- An Extreme Learning Machine is a Reservoir with no memory
- In QRC the input states, the reservoir and the output register are quantum
- A quantum RC can perform classical tasks as well as quantum tasks

Exoplanetary atmospheres retrieval via a quantum extreme learning machine





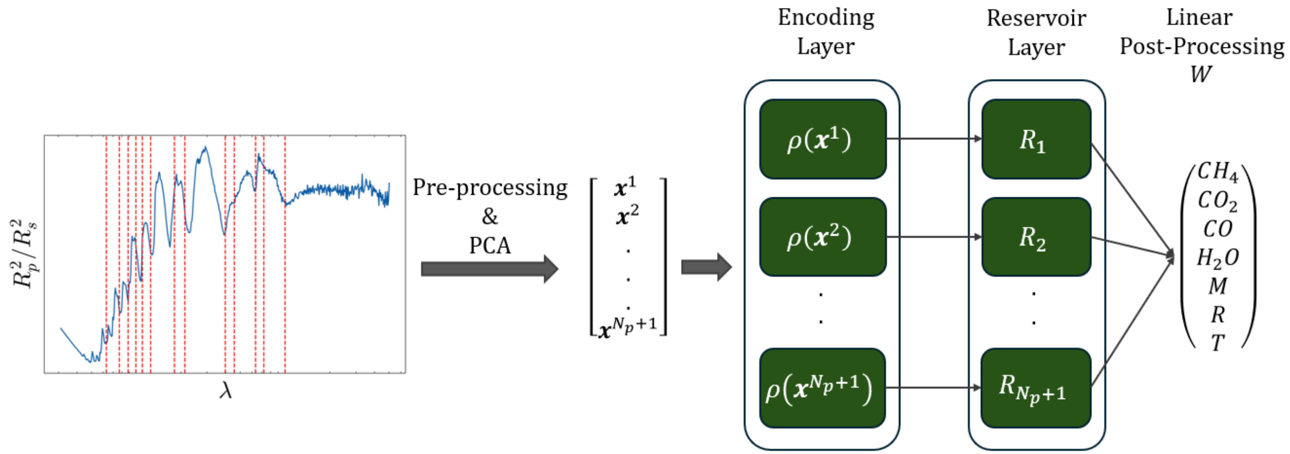


FIG. 5. Results obtained by processing the **JWST** dataset using IBM Fez. The results have been obtained using reservoirs of 5 qubits each and M=5. In this context we considered a dataset of D=4080 spectra, with the 75% used for training and the rest for testing. Both the results obtained on hardware and the finite statistics simulation were obtained with 20000 shots.

Accuracy (%)	CH_4	CO_2	CO	H_2O	M	R	T
Infinite Stat	96.3	86.6	43.8	99.7	78.9	100.0	81.0
Finite Stat	86.4	76.7	39.7	88.5	54.2	100	63.5
IBM Fez	83.6	75.1	39.5	86.2	51.7	100.0	64.5

Project Outcomes & Dissemination

Milestones & Deliverables

- Characterization of Quantum Extreme Learning Machines
- Efficient Exoplanetary atmospheres retrieval via a quantum extreme learning machine
- We plan to extend the technique to the characterization of supernovae remnants

qunipa

https://quantum.unipa.it/

Publications & Conferences

- **State estimation with quantum extreme learning machines beyond the scrambling time M.Vetrano, G.Lo Monaco, L.Innocenti, S.Lorenzo, G.M. Palma; Nature Physics Journal: Quantum Information 11 (1), 2025**
- **Exoplanetary atmospheres retrieval via a quantum extreme learning machine; M Vetrano, T Zingales, GM Palma, S Lorenzo, arXiv preprint arXiv:2509.03617 (Quantum Machine Intelligence, submitted)**
- Poster a QTML2023 Quantum Techniques in Machine Learning Ginevra
- Poster a IQIS24 Italian Quantum Information Science conference Pizzo Calabro
- Poster a IQIS25 Quantum Information Science conference Bologna
- Seminario NES23 Erice, Centro Ettore Majorana
- Seminario alla SIF25 Unipa
- Seminario alla QRC24 Erice, Centro Ettore Majorana

Networking

- First PhD on Quantum Artificial Intelligence @UNIPA, in collaboration with INAF, fondazione Ri.MED, UNIBO, UNIPV, UNINA

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Exoplanetary Atmospheres on Hybrid Architectures

computational framework

high-performance simulation software for hybrid computing architectures to model the complex chemical, climatic, and dynamic evolution of exoplanetary atmospheres;

core derivables

integrating multi-physics processes, from radiation transport to photochemistry, construction of a massive, indexed database of synthetic observables and physico-chemical profiles;

research impact

the database provides a scalable resource for the high-fidelity characterization of exoplanets;

integrated software architecture

CP_Zephyr, high-performance framework that assembles five modular codes, GRACES, CPCHEM, CPAXCES, CPCROSS, CPSPEC, into a single, integrated environmens.

analytic radiative transfer

GRACE

equilibrium chemistry

CPCHEM

non-equilibrium chemistry

CPAXCES

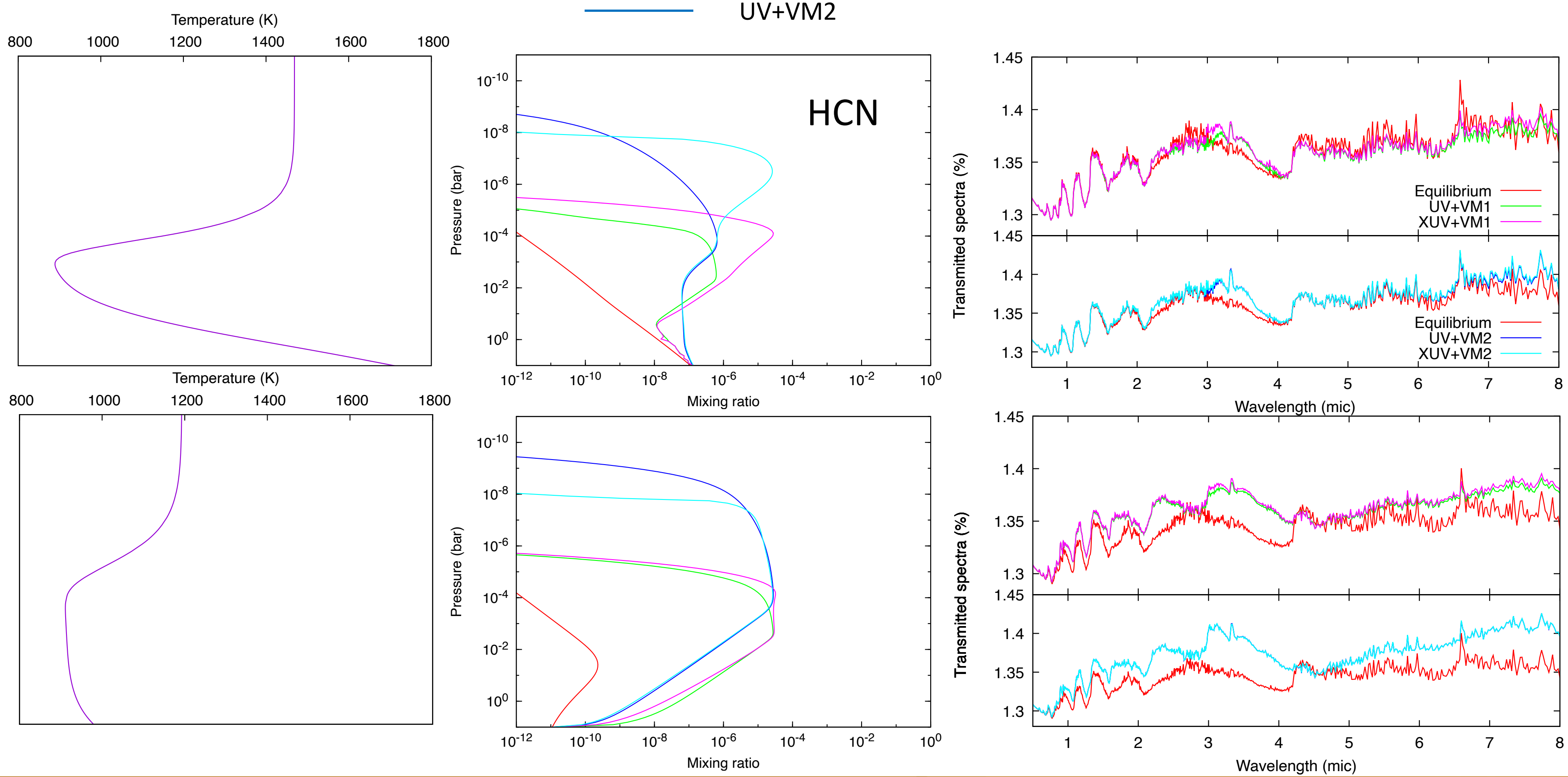
molecular absorption cross-sections

CPCROSS

synthetic transmission spectra

CPSPEC

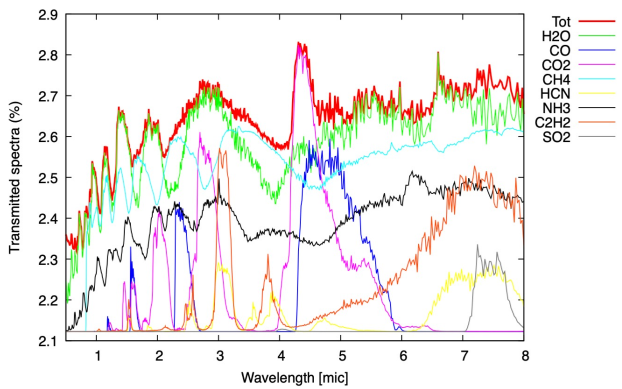
Outcomes



Related publications and talks

- Locci+24, PSJ, 5, 554;
- Biasiotti+26, ApJ, 996, 43;
- La Mura+26, AC, 55, 101077;

- Gaps, Torino 23;
- Ariel Dryrun, Palermo 24 (2);
- SETI, Cagliari 25;
- Molecules and planets in outer galaxies, Firenze 25;
- Ariel, Madrid 2025.



The SpotCCF Tool

SpotCCF

Background & Aims

Stellar activity (e.g. starspots) **deforms** spectrum lines. **SpotCCF** models the cross-correlation function (CCF) to analyze these distortions in active stars.

The model

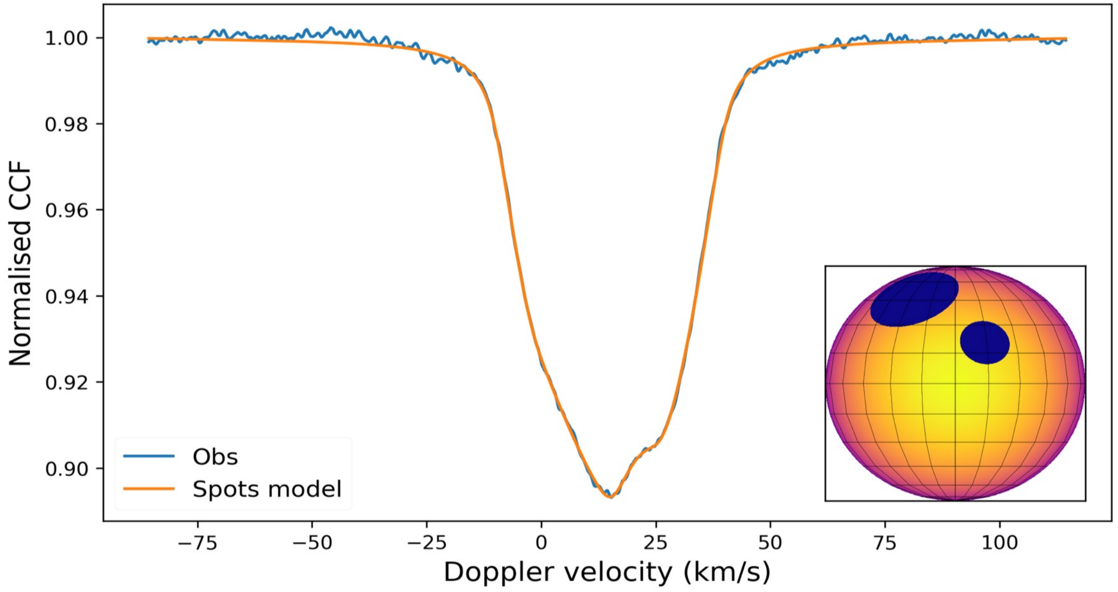
1. **3D spherical mask** to construct the stellar surface
2. **Convolution** of the spectrum of a non-rotating star with the **rotational profile**
3. **Limb-darkening effects** using the law proposed by Claret (2000)
4. **Lorentzian convolution** to account for the CCF wings

Output & Applications

- Estimation of spot geometric parameters (**longitude, latitude, radius**).
- **Precise Radial Velocity (RV) measurement**, corrected for stellar activity.

Impact & Project Relevance

- ✓ **Accurate planetary mass determination** for atmospheric characterization.
- ✓ **Transit spectra correction** via independent stellar mapping.



Di Maio et al. 2024, A&A , 683, A239

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The PAStar Grid

Background & Aims

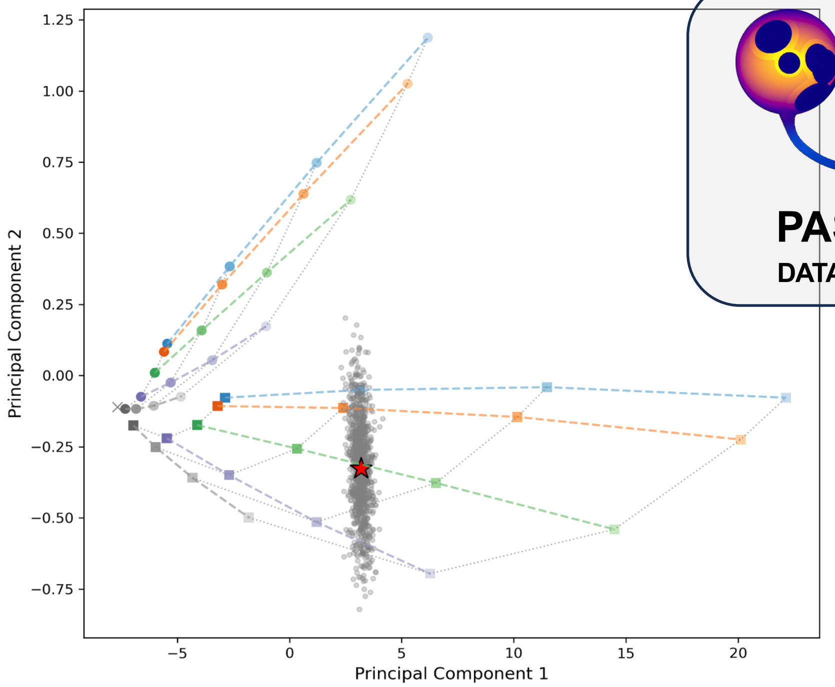
Stellar noise prevents accurate planetary signal extraction.
Building a **grid of simulated active stars** to model and remove this effect.

The Grid Parameters

1. Covers **multiple** stellar **spectral classes**.
2. Simulates activity injecting **1 or 2 spots** on the stellar surface.
3. Explores a vast parameter space **varying spot radii and longitudes**.

Data Access & Project Impact

- ✓ More than **290 000 spectra**
- ✓ **Fully available** to the community via a **dedicated web portal** hosted by **INAF – OAPa** servers.
- ✓ PAStar Grid provides essential simulated data to test and validate extraction tools for current and future facilities



PAStar
DATABASE

Di Maio et al., in preparation

Applications

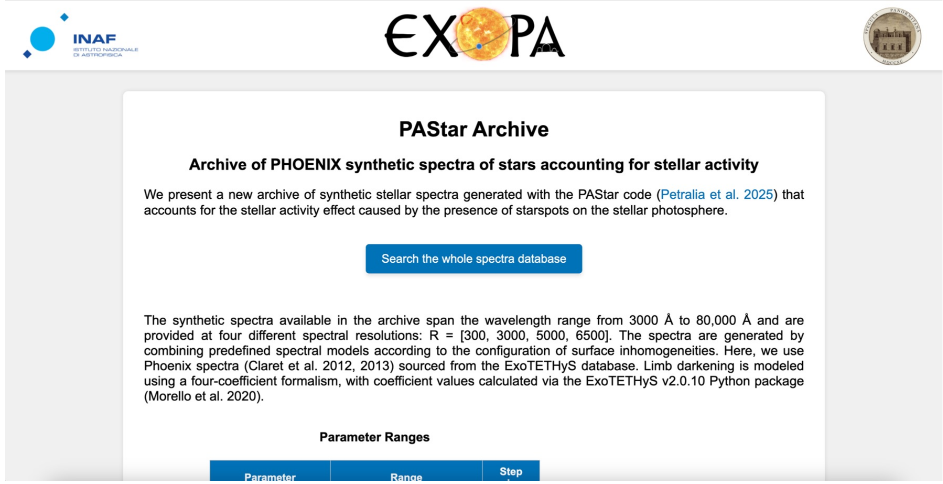
- ➢ **Principal Component Analysis** (PCA) applied to the synthetic grid.
- ➢ **Isolate** and **characterize the spectral variations** caused by stellar activity
- ➢ Extracts the main components to **model and subtract the stellar noise from observed data**.

Project Outcomes & Dissemination

Milestones & Deliverables

- Development of signal extraction codes (**SpotCCF**)
- Creation/distribution of simulated spectra grids (**PAStar Grid**).
- Public release of the **PASTar Grid on a dedicated website** hosted on INAF-OAPA servers.

http://pastar.oapa.inaf.it



Publications & Conferences

- **Di Maio et al. 2024, A&A , 683, A239 (SpotCCF tool)**
- **Di Maio et al. , in preparation (PAStar Grid)**
- Biagini, Petralia, Di Maio, et al., 2024, A&A, 690, A386
- Biagini, Cracchiolo, Petralia, et al. 2024, MNRAS 530, 1054–1065
- Sicilia, Scandariato, Guilluy, et al., 2024, A&A, 687, A143
- D'Arpa, Saba, Borsa, Fossati, et al., 2024, A&A, 690, A237
- Bonomo, Naponiello, Sozzetti, et al, 2026, A&A
- Talk@23° GAPS Meeting (Catania 2025)
- Talk @ 13° Young Reseacher Meeting (Palermo 2025)
  - **Awarded Best Oral Contribution**
- Talk @Ariel Consortium Meeting (Leiden 2025)
- Talk @113° Congresso Nazionale della SIF (Palermo 2025)
- Poster @ Towards Other Earths III (Porto 2023)
- Poster @ ExoItaly (Roma, 2025)

Networking

- ➢ Developed strong strategic networks at national and international levels.
- ➢ Active collaborations with major exoplanetary consortia and space missions, including **GAPS** and **ESA-Ariel**.