Applying AI to non-linear Physics

Nathaniel Saura[1]

Journée IA et sciences physiques

1- Laboratoire PIIM, Aix-Marseille Université, UMR 7345, France

1: Presentation of the team

- Merging of PCiAI and PATP
    - Sadri **Benkadda**
    - Peter **Beyer**
    - Mohammed **Koubiti**
    - Nathaniel **Saura**
    - David **Garrido**
- Active collaboration with CEA, Osaka University, American University of Beyrouth
- Future collaboration with Tokyo University, University of Seattle, ...

Plasma and fusion

- Instead of nuclear fission, **nuclear fusion** ⇒ more energy, less radioactivity but: extreme conditions, non-linearity, turbulence...
- **Tokamak**: fusion reactor. Strong magnetic fields instead of gravity.
- **Confinement**: keeping the plasma's central region sufficiently hot and dense for nuclear fusion.
- **Achieving efficient nuclear fusion**: maintaining high confinement mode ⇒ more energy produced

- **Impurities**: weakly ionized ("cold") atoms torn from the Tokamak walls due to its interactions with the hot plasma
- Impurities migrate from wall to core this breaks the confinement

Our topics

Our main focus

- Applying AI to overcoming the fusion's barriers
  - Towards understanding the origin of the degradation of the confinement
    - Remove signal corruption to enhance measurement devices
    - Better identify "cold elements" coming from the edge ⇒ control
    - Speed up simulations and/or develop models
- Non-linear physics (Astrochemistry, Fluid mechanics)

Secondary topics

- Application of AI in Ecology
- Modeling energy community evolution using game theory
- Automatic molecular identification

Improving the identification of ions in the presence of strong noise

- In spectroscopy, the noise degrades the accuracy and confidence of element recognition methods
  - Corrupts data
  - Challenges the usability of signal processing methods
- CNN have been widely used in the context of noisy images
  - Disentangling noise and signal to keep the coherent part
  - Auto-encoder (CAE) vs Denoising CNN (DnCNN) based on residual

Use and compare CNN architectures to improve the ion identification

Considering strongly corrupted signals:

- Improve the PSNMF identification confidence using the two approaches
- Compare the noise removing capacity and the learning strategy induced by the architecture

DnCNN and CAE

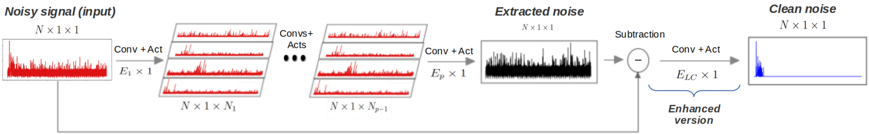


Figure 1: DnCNN [?] and the enhanced one [?] featuring a residual connection.

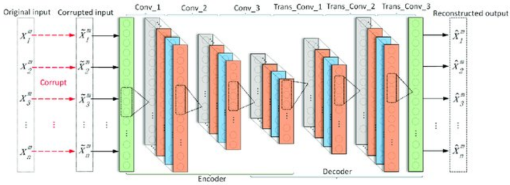


Figure 2: CNN Encoder-decoder architecture example [?]

Signal denoising comparisons (N0; SNR$= -1$)

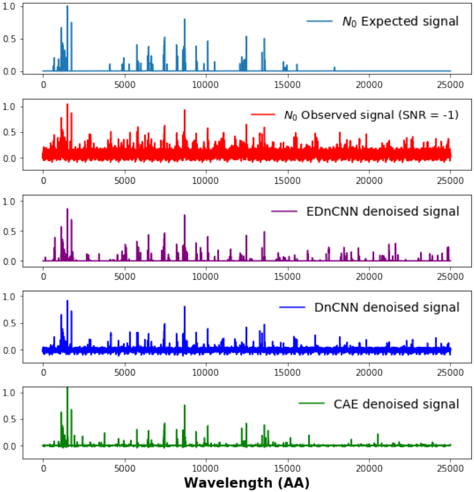


Figure 3: Denoising comparisons for N0

Signal denoising comparisons (W2; SNR$= -1$)

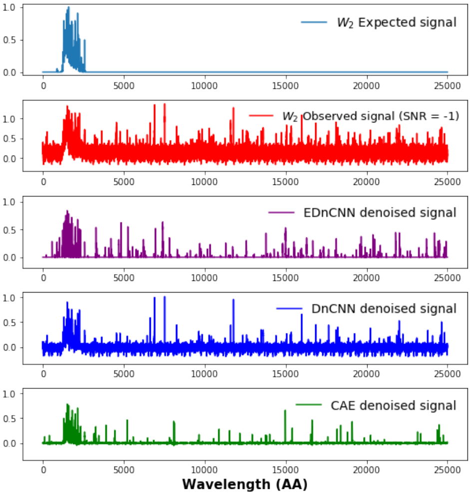


Figure 4: Denoising comparisons for W2

PSNMF improvement (SNR$= -1$)

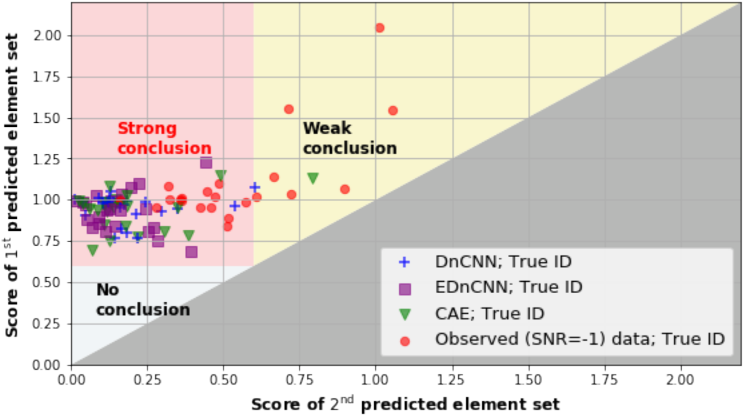


Figure 5: Noise described by SNR$= -1$

PSNMF improvement (SNR$= -5$)

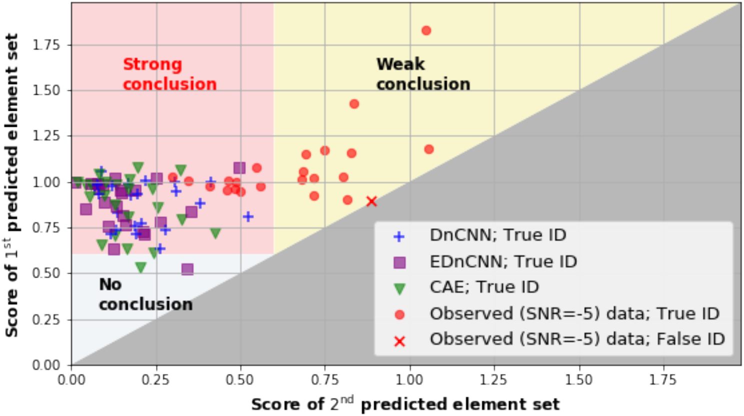
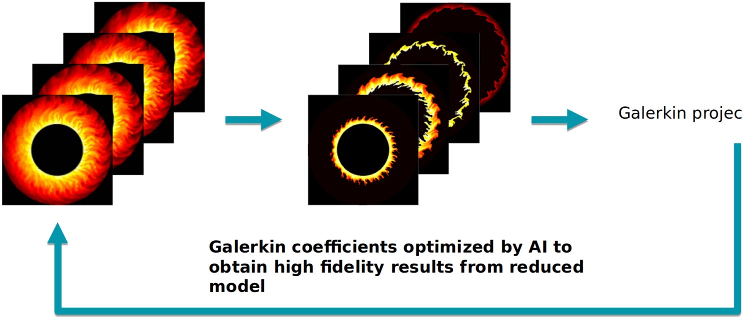


Figure 6: Noise described by SNR$= -5$

AiPoG - Global Framework



Collection of snapshots coming from the PDE

POD (proper orthogonal decomposition)

Galerkin projection, ODEs

Galerkin coefficients optimized by AI to obtain high fidelity results from reduced model

Figure 7: Framework: how to tackle PDEs

Learning the dynamics of a system

Using a well-designed neural network, we can learn the time rate evolution of a system

Dynamical system: Predator-Prey

$$\frac{dE}{dt} = 2E\left(\gamma - \alpha_1 E - \alpha_2 U\right),$$
$$\frac{dU}{dt} = 2U\left(-\mu + \alpha_3 E\right).$$

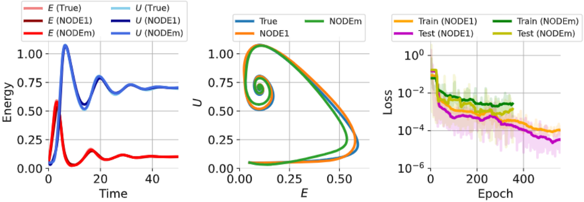


Figure 8: Training to learn the system's dynamics

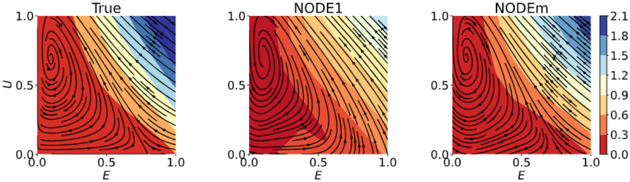


Figure 9: Comparison between phase portraits

Example of AiPoG on Hasegawa-Wakatani

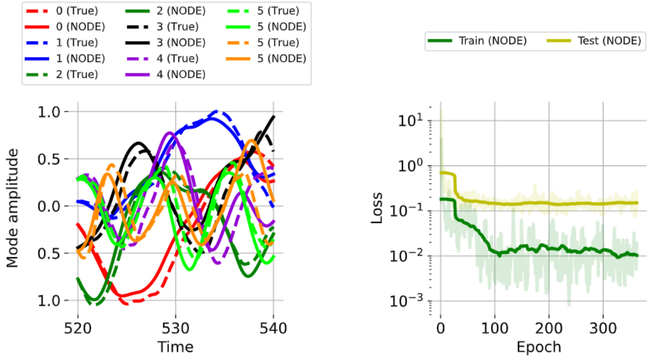


Figure 10: Training to learn the ODE systems obtained from the Galerkin Projection onto the extracted POD modes

Example of AiPoG on Hasegawa-Wakatani

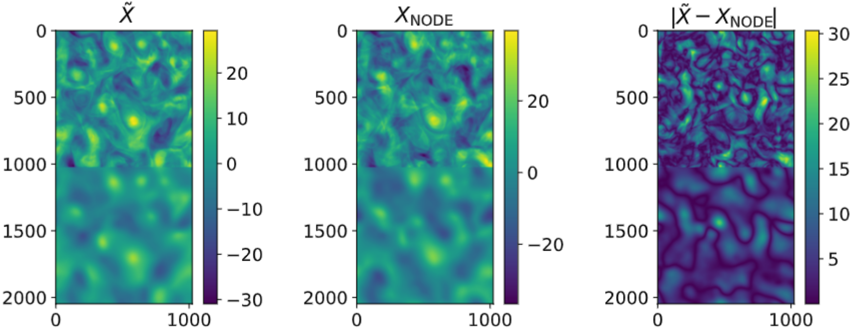


Figure 11: Comparison of expected and predicted fields

Ongoing and future works

- **Improving** AiPoG application to chaotic systems and other PDEs
- **Predicting** particle cluster with specific properties
- **Enhancing** spectroscopic analysis (CEA)
- **Developing** a machine-learning-based interatomic potentials (Osaka University)
- **Automatic** identification of a molecule and its atomic composition (ASTRO, Osaka University)
- Application of Game Theory to enhance **interpretability** of NN
- And more

Greetings

Thank you for your attention