Forum TERATEC

Evaluer l'aléa sismique en France grâce à un méta-modèle neuronal

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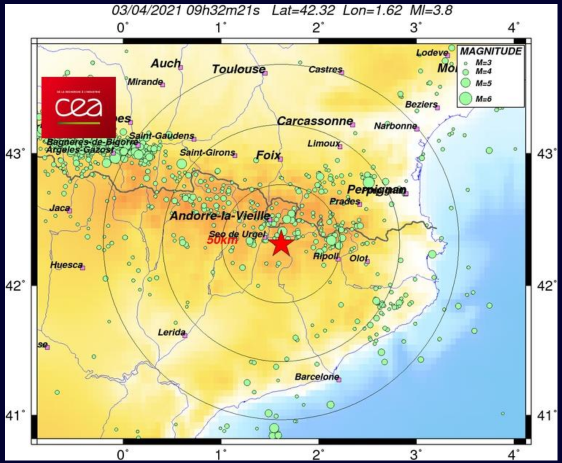
{OPEN}

CEA-DAM Île de France

- **Conception et garantie des charges nucléaires pour la dissuasion :** programme simulation
- **Analyse, surveillance, alertes :** lutte contre la prolifération nucléaire et le terrorisme, séismes, tsunami, essais nucléaires
- **Co-développement avec Atos des calculateurs « Défense » du Très Grand Centre de Calcul**
- **Ingénierie nucléaire des infrastructures de la DAM :** de la conception au démantèlement

TGCC
Très Grand Centre de calcul du CEA

Analyse & surveillance sismique



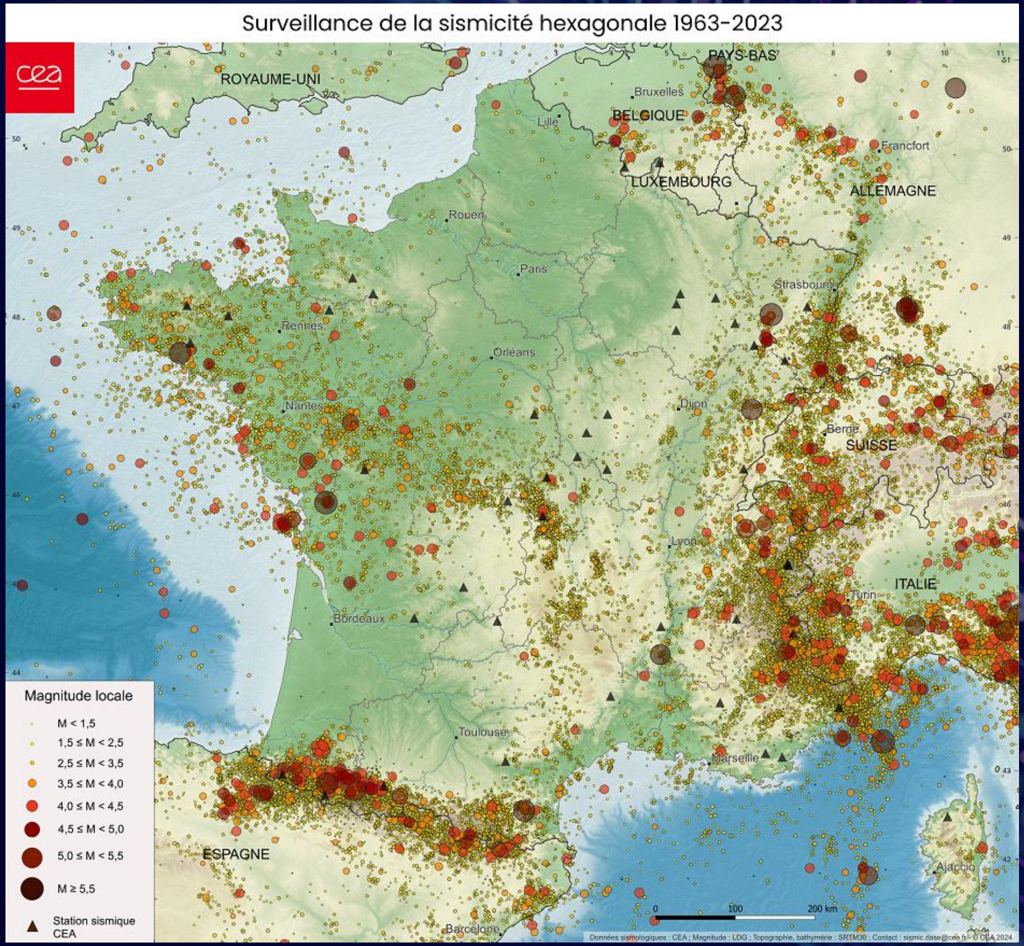
Missions :

- Alerte aux forts séismes (sécurité civile) et service aux grands opérateurs nationaux (SNCF, EDF,…)
- Alerte tsunamis (CENALT)
- Expertise au service de l'Agence Internationale de l'Energie Atomique (AIEA) et de l'Organisation du traité d'interdiction complète des essais nucléaires (OTICE).

- Suivi des événements sismiques
- Conception de capteurs et réseaux associés
- Détection opérationnelle de tout événement sismique & tsunami : analyse + émission d’alerte aux pouvoirs publics
- Etude de l’aléa sismique

Analyse & surveillance sismique

Réseau de surveillance pour la France métropolitaine : 44 stations du CEA et environ 180 stations Epos-France, accessibles en temps réel.

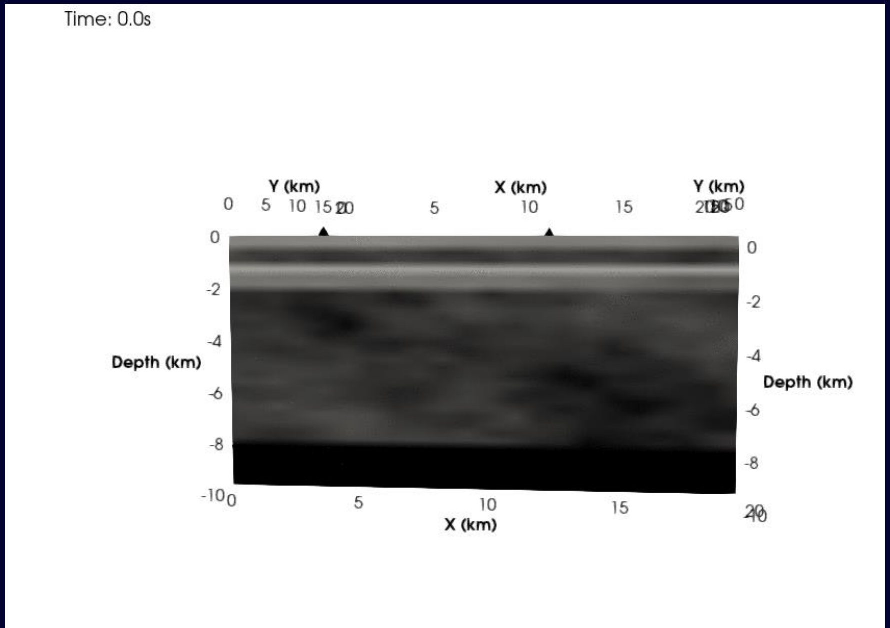


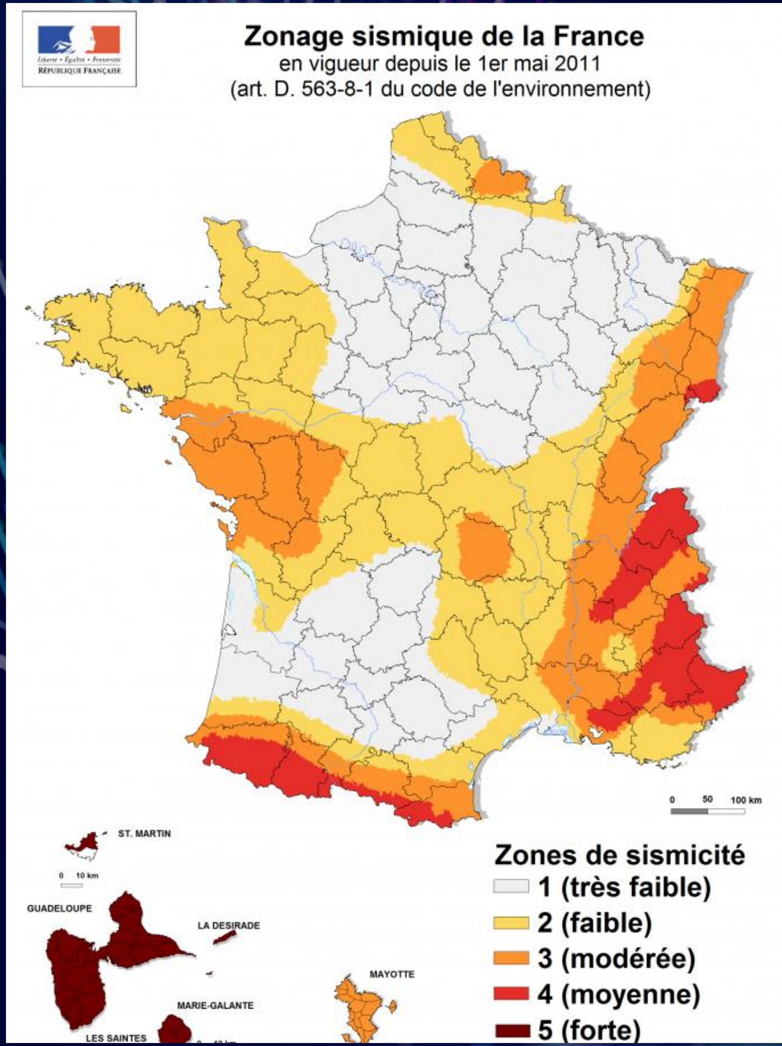
Environ 100 000 séismes, localisée par les analystes du CEA depuis les années 60.

Seismic hazard assessment

- Typical question: "What is the maximum ground motion acceleration that has a 10% probability of being observed in the next 50 years in this region?"
- High-fidelity 3D numerical simulations are necessary to complement recordings, especially in low-to-moderate seismicity regions.

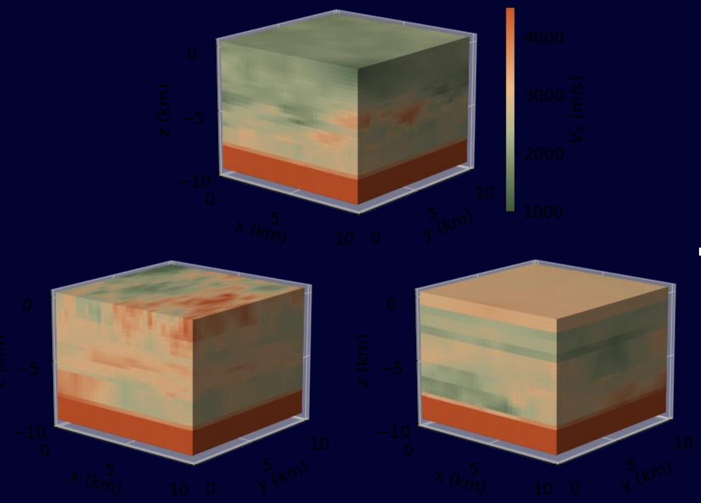
→ We need a surrogate model to reduce computational costs, allowing uncertainty analysis





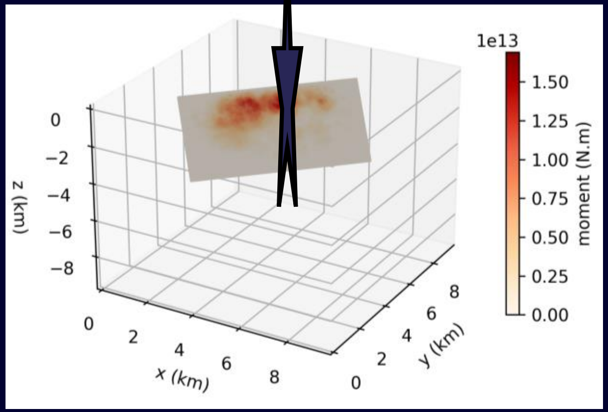
Formulation of the problem

geological properties



source position (x_s)

source orientation (θ_s)

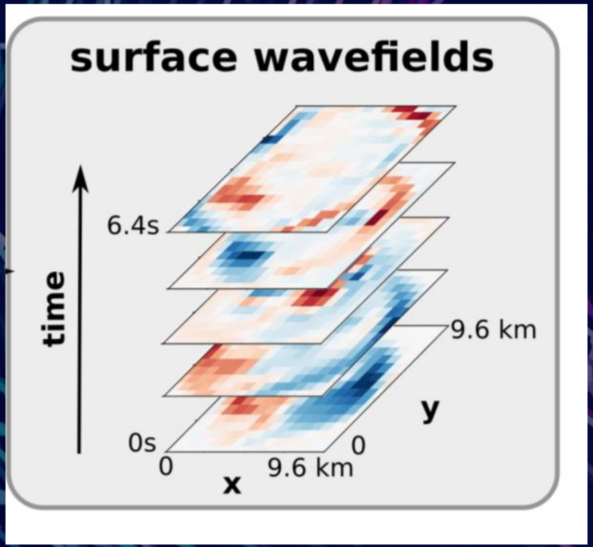


elastic wave equation

$$\rho \frac{\partial^2 \boldsymbol{u}}{\partial t^2} - \nabla \cdot \sigma(\boldsymbol{u}) = f(\boldsymbol{x}_s, \boldsymbol{\theta}_s)$$

Spectral element solver SEM3D

Publicly available on
Recherche Data Gouv



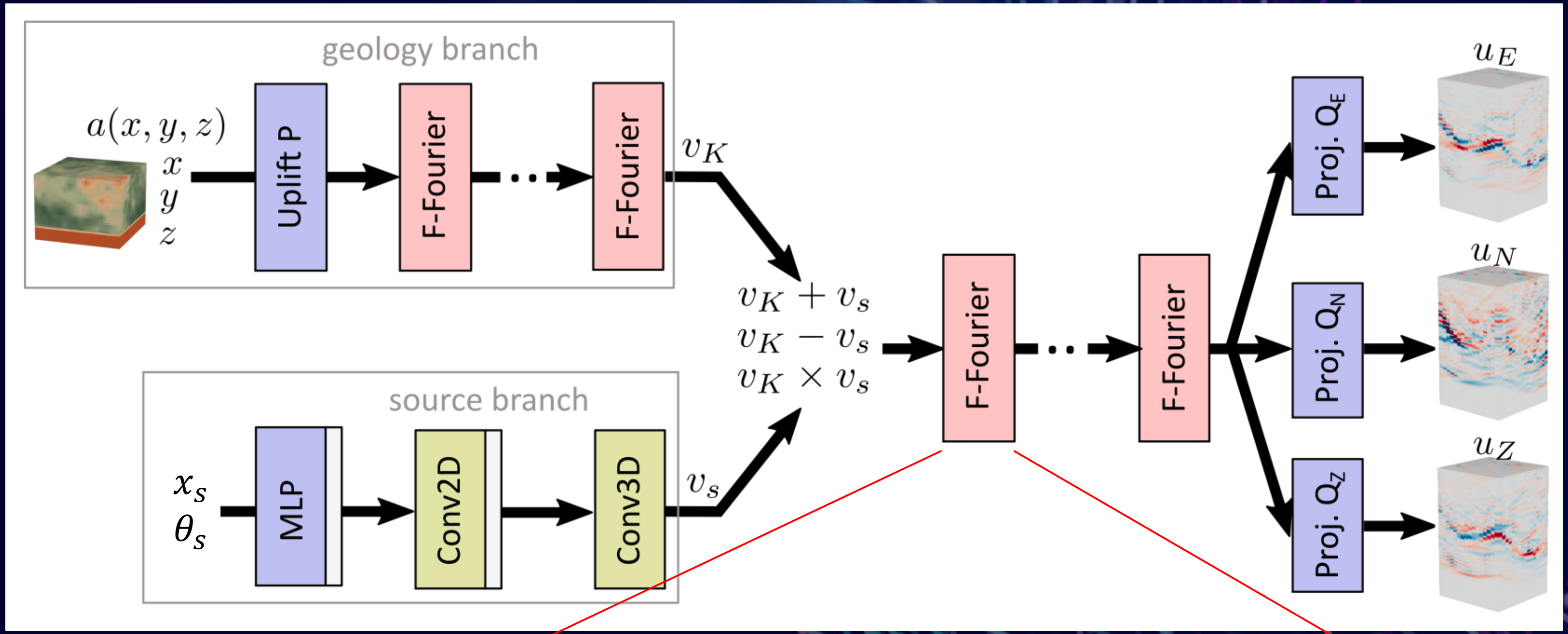
30,000 simulations
680,000 CPU.hours

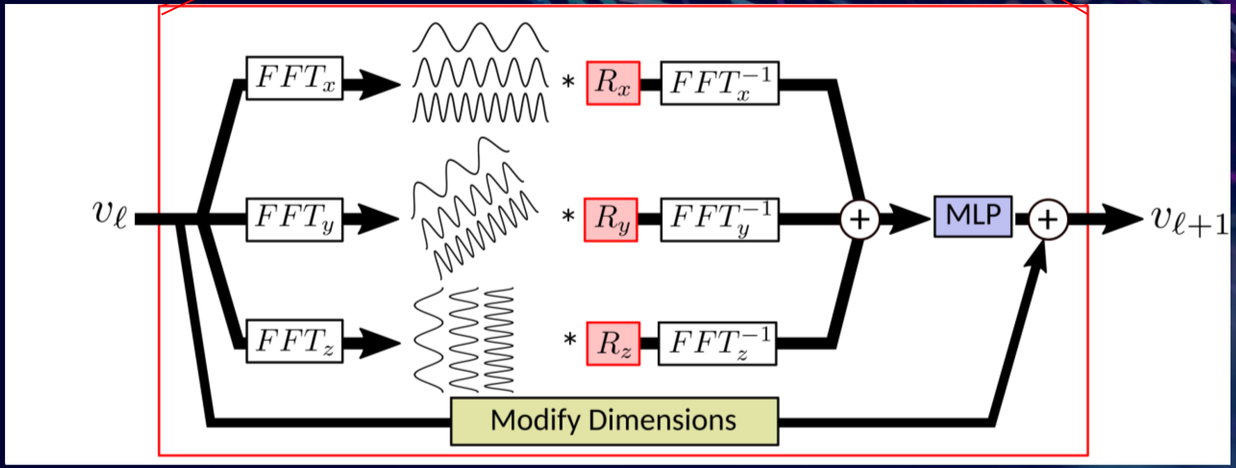
[Lehmann et al., *ESSD*, 2024]

Multiple Input Fourier Neural Operator (MIFNO)

- Neural Operators extend Neural Networks to **functional spaces.**
- FNO learns the **frequential representation** of the PDE solution.

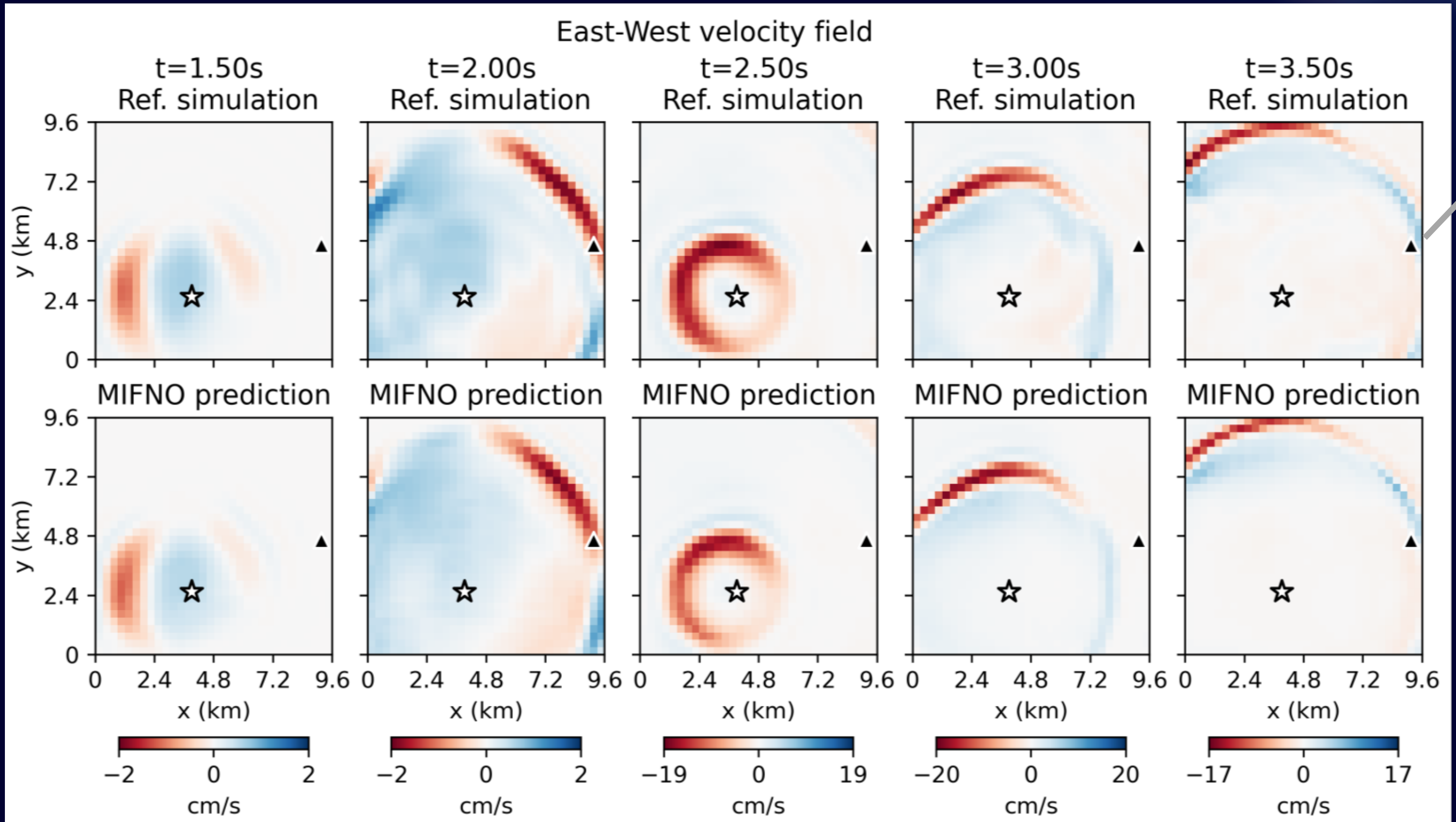
Training with 30,000 simulations
29h on 4 GPUs

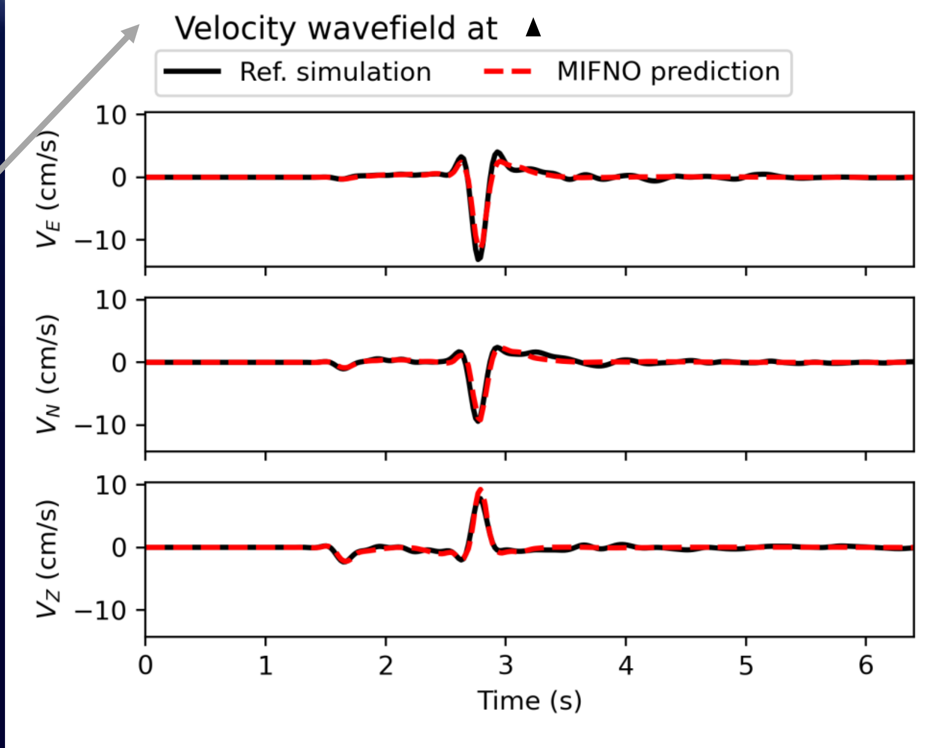




[Lehmann et al., *CMAME*, 2024]

Prediction for a new geology

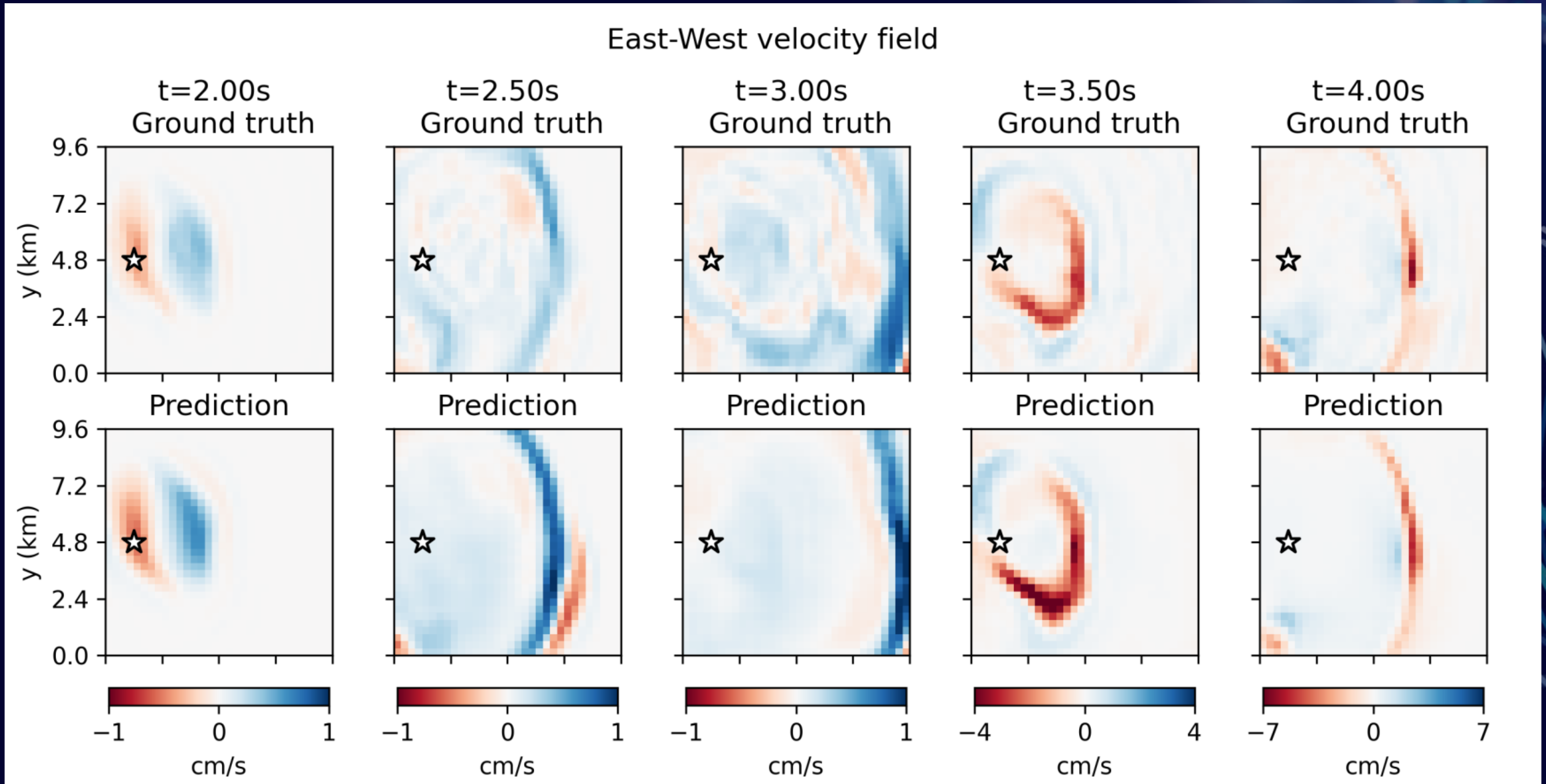




- ✓ **Wave arrival times are very accurate**
- ✓ **Main fluctuations are correctly captured**
- → **Small-scale features & small amplitudes more difficult**

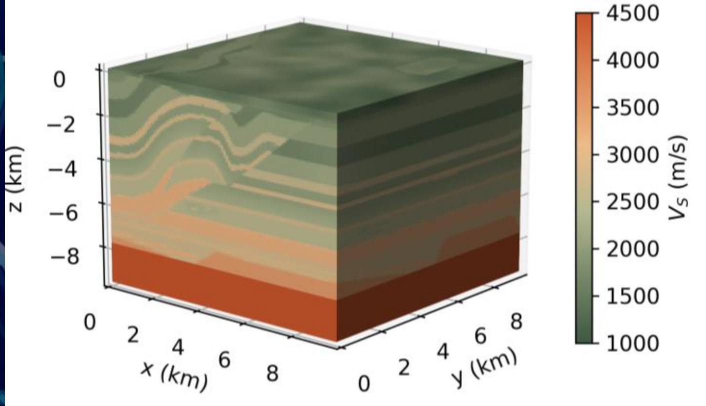
[Lehmann et al., *CMAME*, 2024]

Generalization to a realistic geology



Marmousi model

[Aminzadeh et al.1997]



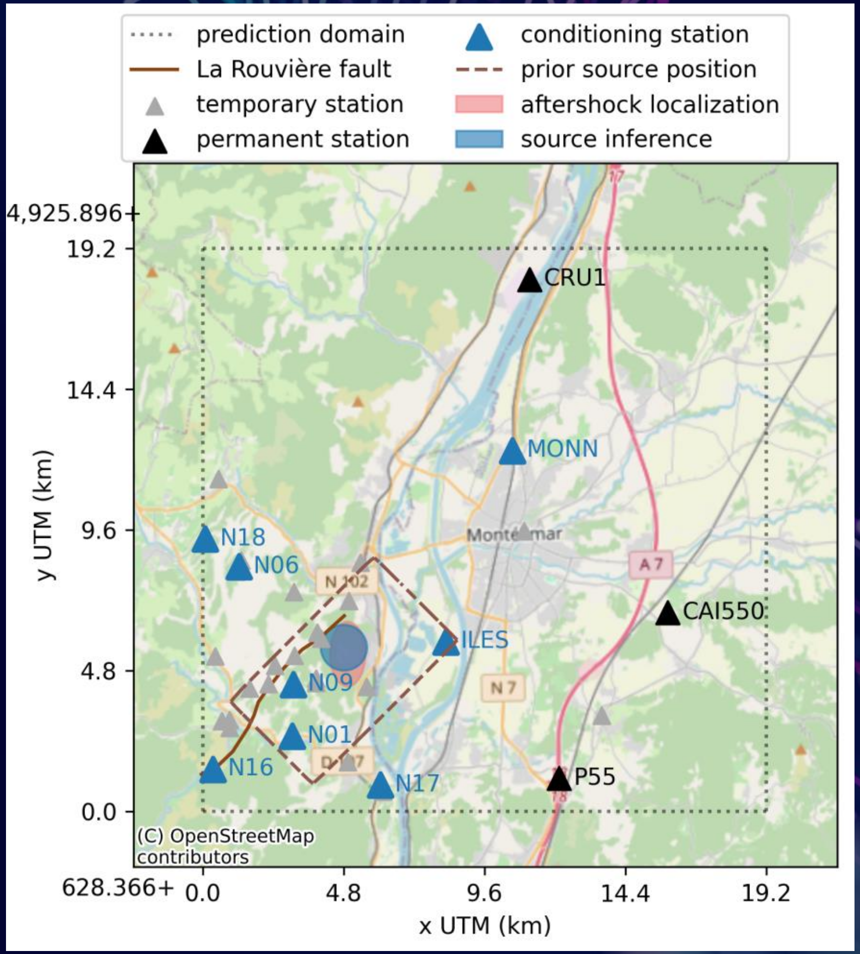
- ✔ **Predictions are good for most sensors.**
- → **Expected lack of small-scale fluctuations**

[Lehmann et al., *CMAME,* 2024]

Transfer Learning

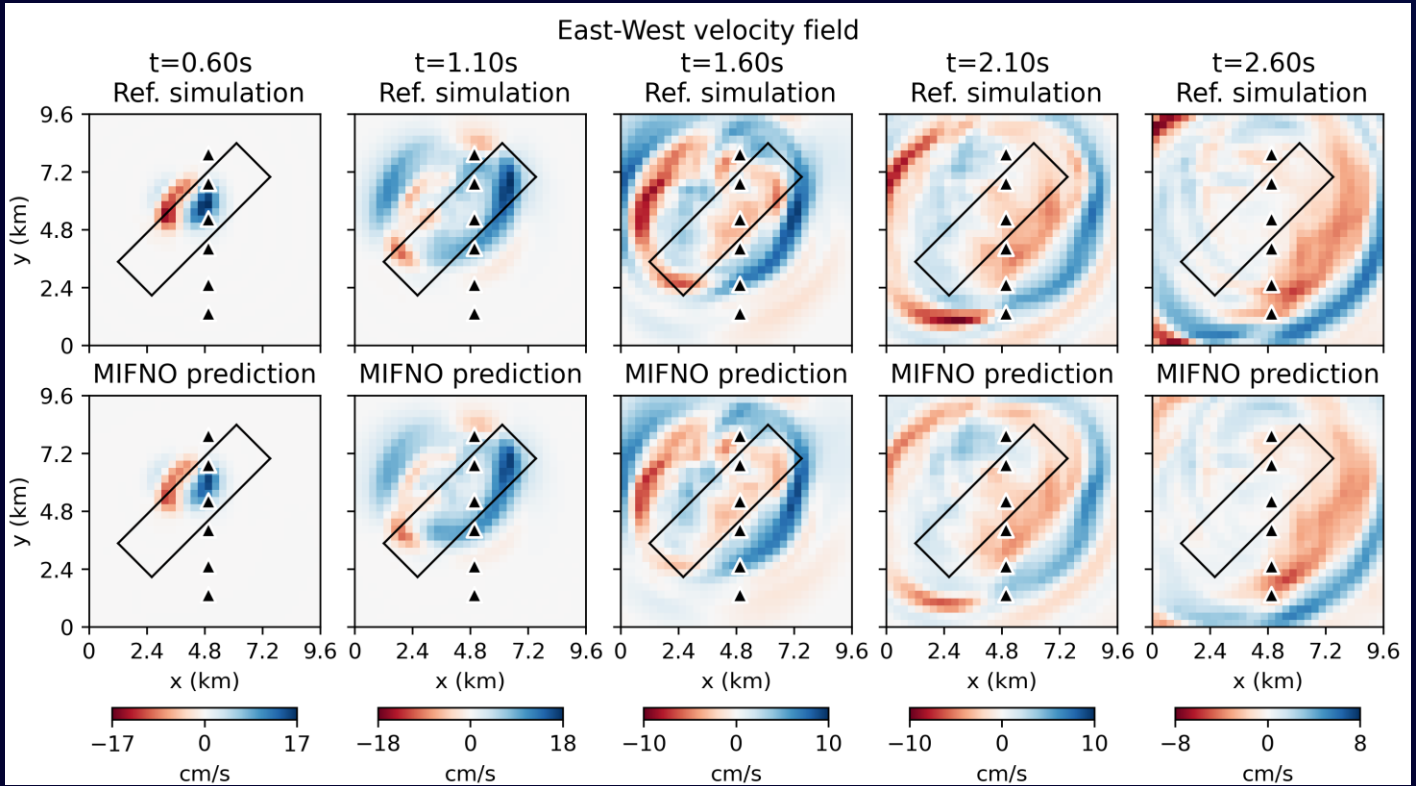
- ➢ **Improve predictions by focusing on a case study: Le Teil earthquake (Ardèche, 2019)**
- ➢ **Transfer learning database is smaller and has less variability.**

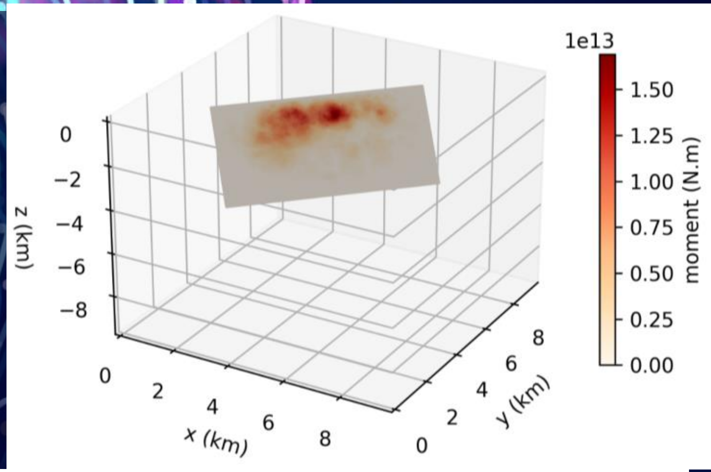
→ **Less computational efforts (~500 specific simulations)**

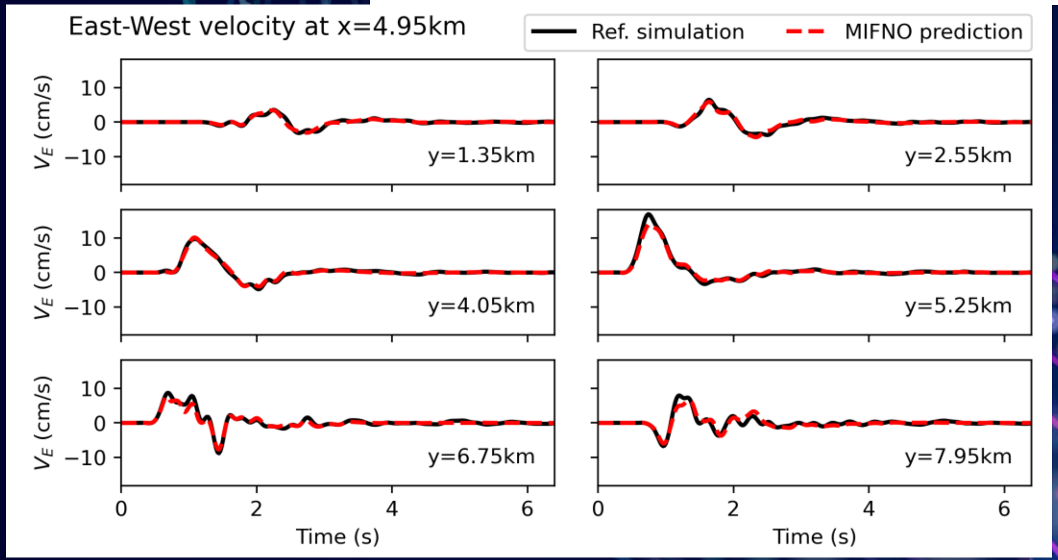


Fault prediction

Superposition principle → Predict ground motion from the dynamic fault rupture







- **Predicts small-scale features and complex temporal dynamics**
- **100% excellent phase and 85% excellent envelope *Goodness-Of-Fit***

Conclusion

- MIFNO is an accurate surrogate model to predict source-dependent PDE solutions in 3D

  → Efficient uncertainty quantification with energy costs /1000

- Posterior distributions of quantities of interest conditioned on observations

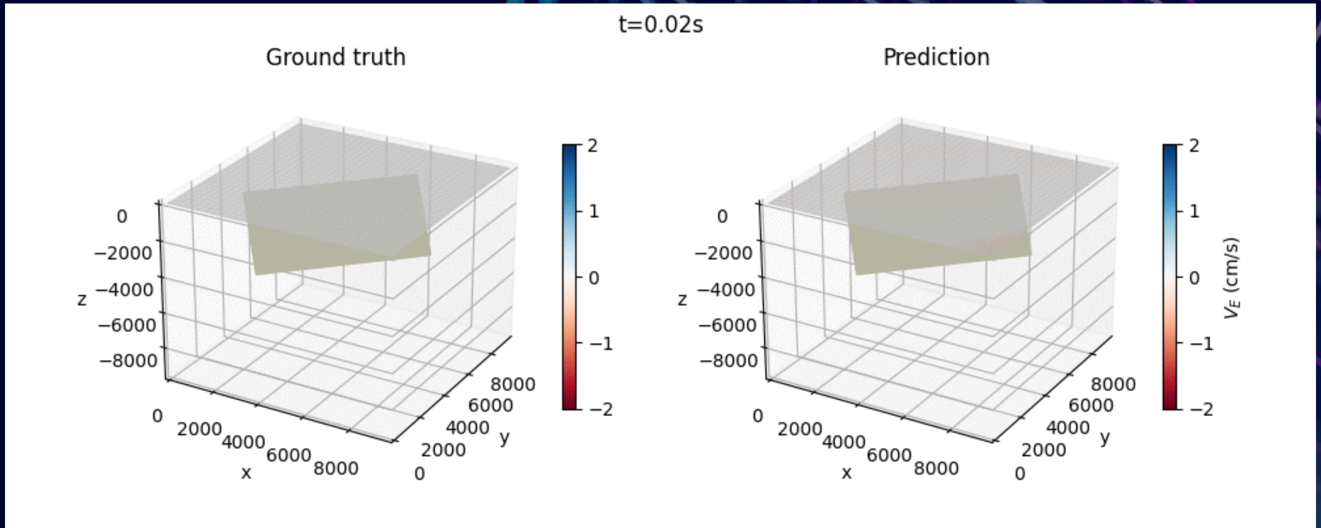
  → Data-informed digital twin

- Important step towards integrating scientific machine learning into seismic hazard analyses

→ Sampling high-dimensional geologies

→ Full seismic hazard analyses with source model

→ Apply to other physical problems



Publications

[1] Lehmann, F., Gatti, F., Bertin, M., Clouteau, D. (2022), Machine learning opportunities to conduct high-fidelity earthquake simulations in multi-scale heterogeneous geology, Frontiers in Earth Science, 10, p. 2194

[2] Lehmann, F., Gatti, F., Bertin, M., Clouteau, D. (2023), Advantages and promises of deep neural operators for the prediction of wave propagation, the 23th EGU General Assembly, doi:10.5194/egusphere-egu23-5068

[3] Lehmann, F., Gatti, F., Bertin, M., Clouteau, D. (2023), Fourier Neural Operator Surrogate Model to Predict 3D Seismic Waves Propagation, 5th International Conference on Uncertainty Quantification in Computational Sciences and Engineering, https://doi.org/10.1016/j.cma.2023.116718

[4] Lehmann, F., Gatti, F., Bertin, M., Clouteau, D. (2023), Seismic hazard analysis with a Factorized Fourier Neural Operator (F-FNO) surrogate model enhanced by transfer learning, NeurIPS 2023 AI for Science Workshop, https://openreview.net/forum?id=xiNRyrBAjt

[5] Lehmann, F., Gatti, F., Bertin, M., Clouteau, D. (2024), Synthetic ground motions in heterogeneous geologies from various sources: the HEMEW-3D database, Earth System Science Data, 16(9), https://doi.org/10.5194/essd-16-3949-2024

[6] Lehmann, F., Gatti, F., Bertin, M., Clouteau, D. (2024), A deep learning-based earthquake simulator: from source and geology to surface wavefields, EGU General Assembly 2024, https://doi.org/10.5194/egusphere-egu24-14438

[7] Lehmann, F., Gatti, F., Bertin, M., Grenié, D., Clouteau, D. (2024), Uncertainty propagation from crustal geologies to rock-site ground motion with a Fourier Neural Operator, European Journal of Environmental and Civil Engineering, https://doi.org/10.1080/19648189.2024.2393883

[8] Lehmann, F., Gatti, F., Bertin, M., Clouteau, D. (2024), 3D elastic wave propagation with a factorized Fourier neural operator (F-FNO), Computer Methods in Applied Mechanics and Engineering, 420, https://doi.org/10.1016/j.cma.2023.116718

[9] Lehmann, F. (2024), A surrogate model of elastic wave propagation to quantify uncertainties in seismic hazard analysis, PhD manuscript, Université Paris-Saclay, HAL Id : tel-04697410