A neural network-based observation operator for weather radar data assimilation

PROJECT ACRONYM
3DVarHNN

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Co-funded by The European Union

VIPAVA, 09 October 2024

OUTLINES

1. INTRODUCTION →
   - Deterministic Chaos in Atmosphere
   - Data Assimilation
2. THE 3D-VAR COST FUNCTION
3. METHODOLOGY AND OBJECTIVE OF THE PROJECT
4. CONCLUSIONS

THE DETERMINISTIC CHAOS

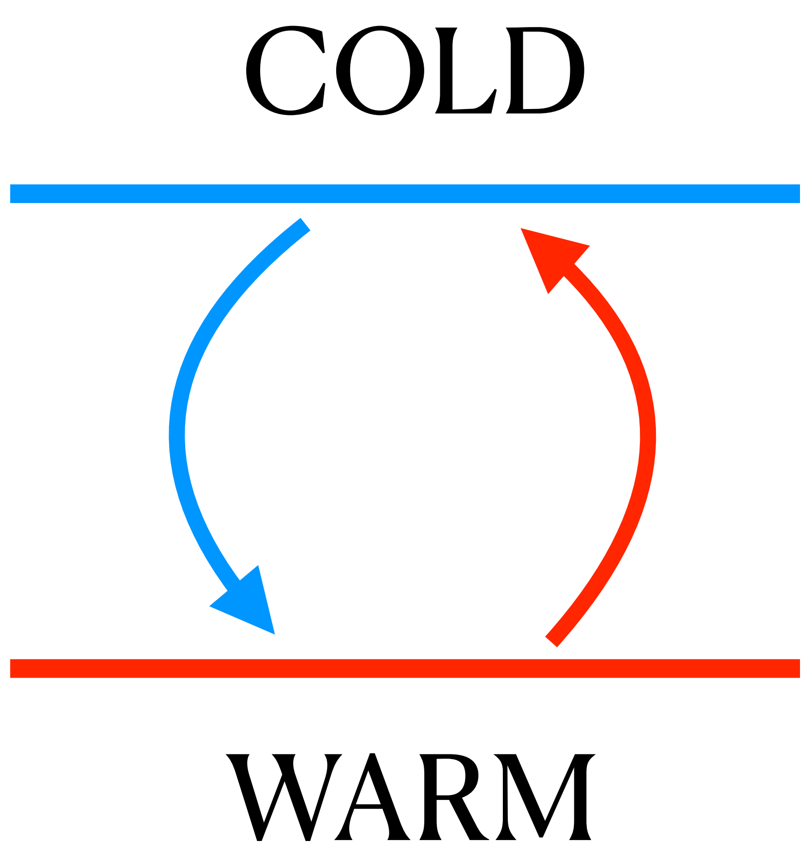
THE LORENZ63 MODEL IS A CONVECTIVE SYSTEM OF EQUATIONS

IT IS A SIMPLIFICATION OF NAVIER-STOKES EQUATIONS.

$$\frac{dx}{dt} = \sigma(y - x)$$

$$\frac{dy}{dt} = -xz + \rho x - y$$

$$\frac{dz}{dt} = xy - \beta z$$



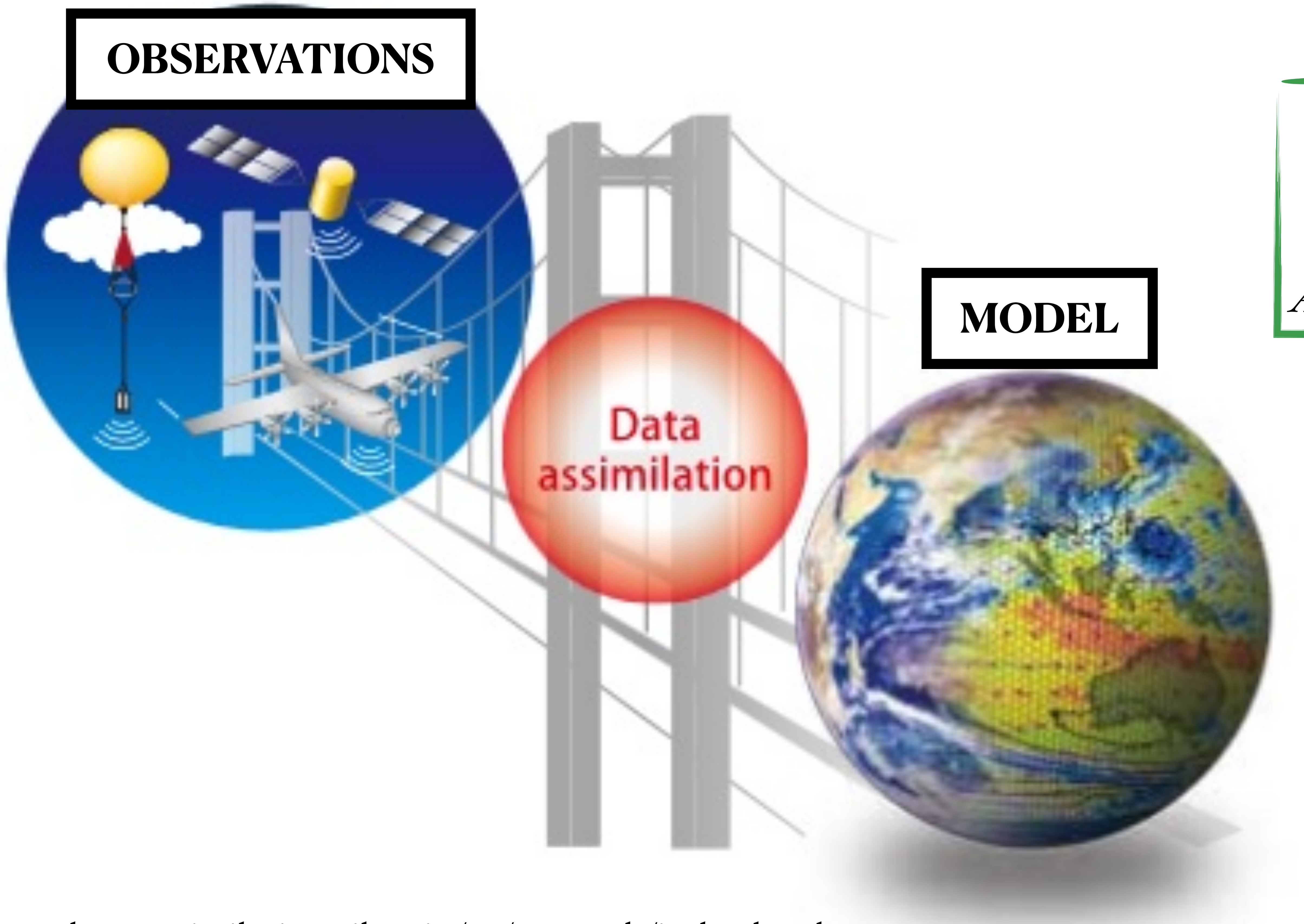
THE BUTTERFLY EFFECT

$X_{0_{TRUE}}$ = [10.000, 10.000, 10.000]

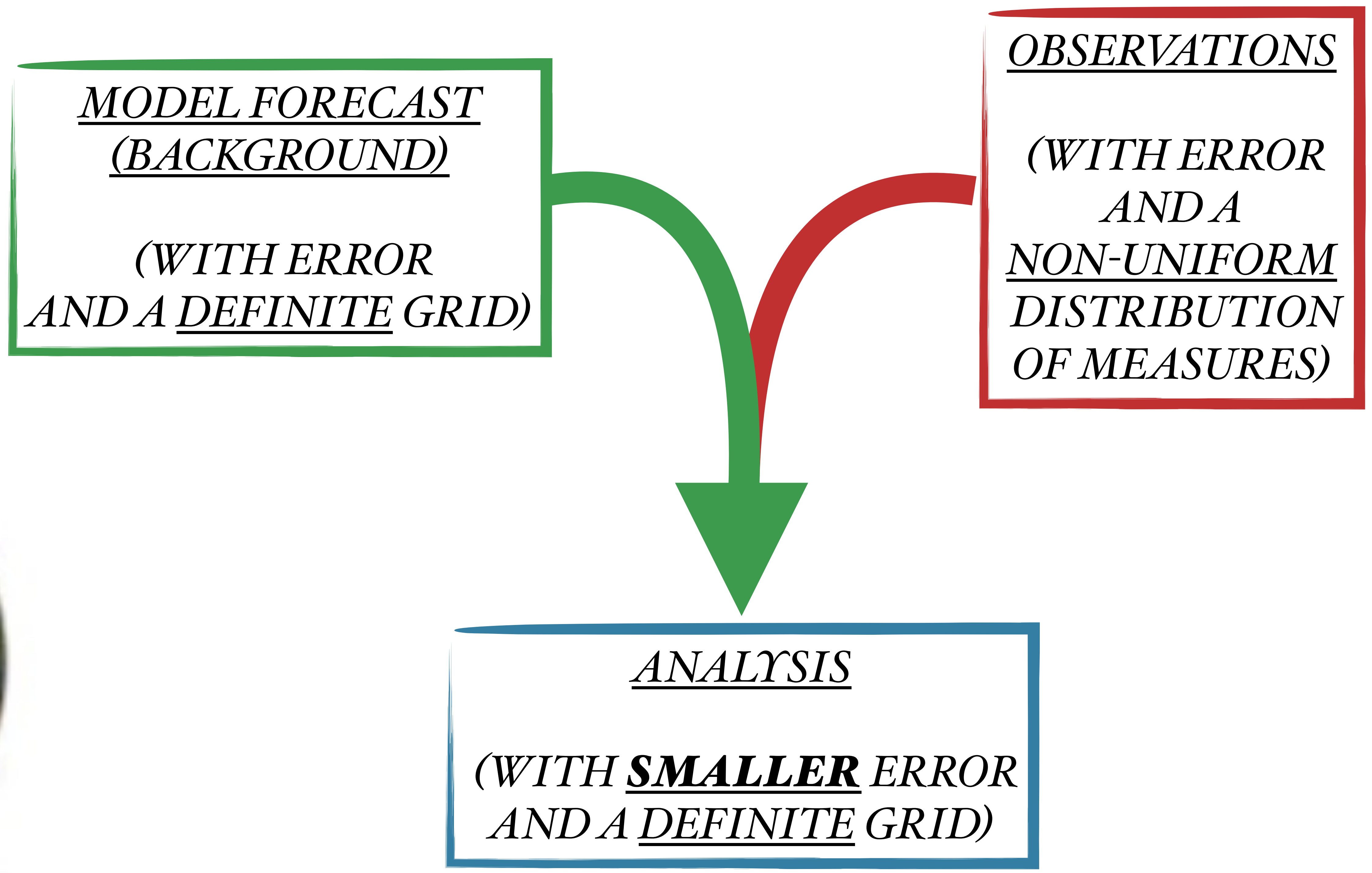
$X_{0_{FORECAST}}$ = [10.001, 10.001, 10.001]

Lorenz, Edward N. "Deterministic nonperiodic flow." *Journal of atmospheric sciences* 20.2 (1963): 130-141.

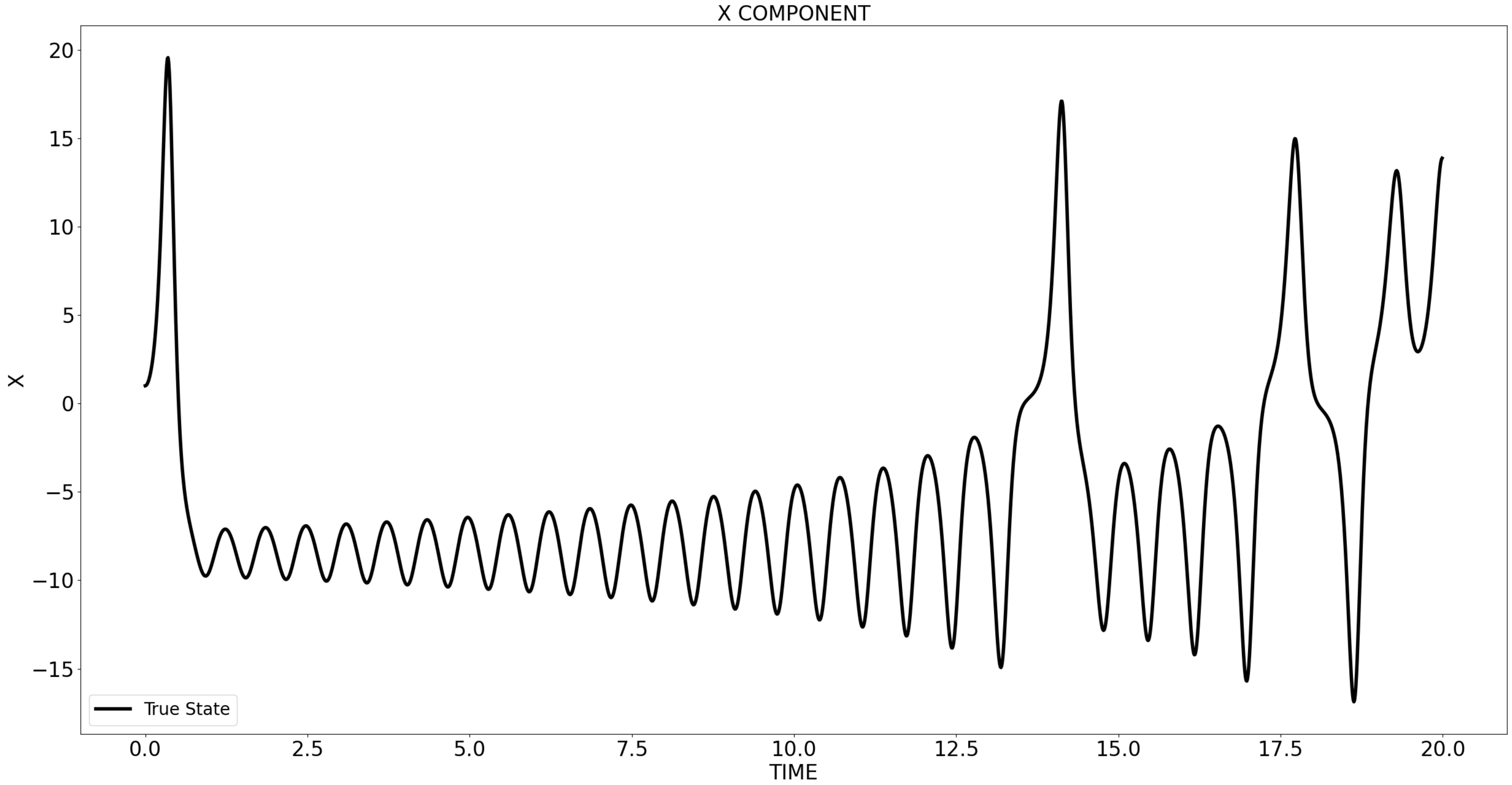
DATA ASSIMILATION
THE BRIDGE BETWEEN MODEL AND OBSERVATIONS



https://www.data-assimilation.riken.jp/en/research/index.html



DATA ASSIMILATION APPLICATION ON THE LORENZ SYSTEM



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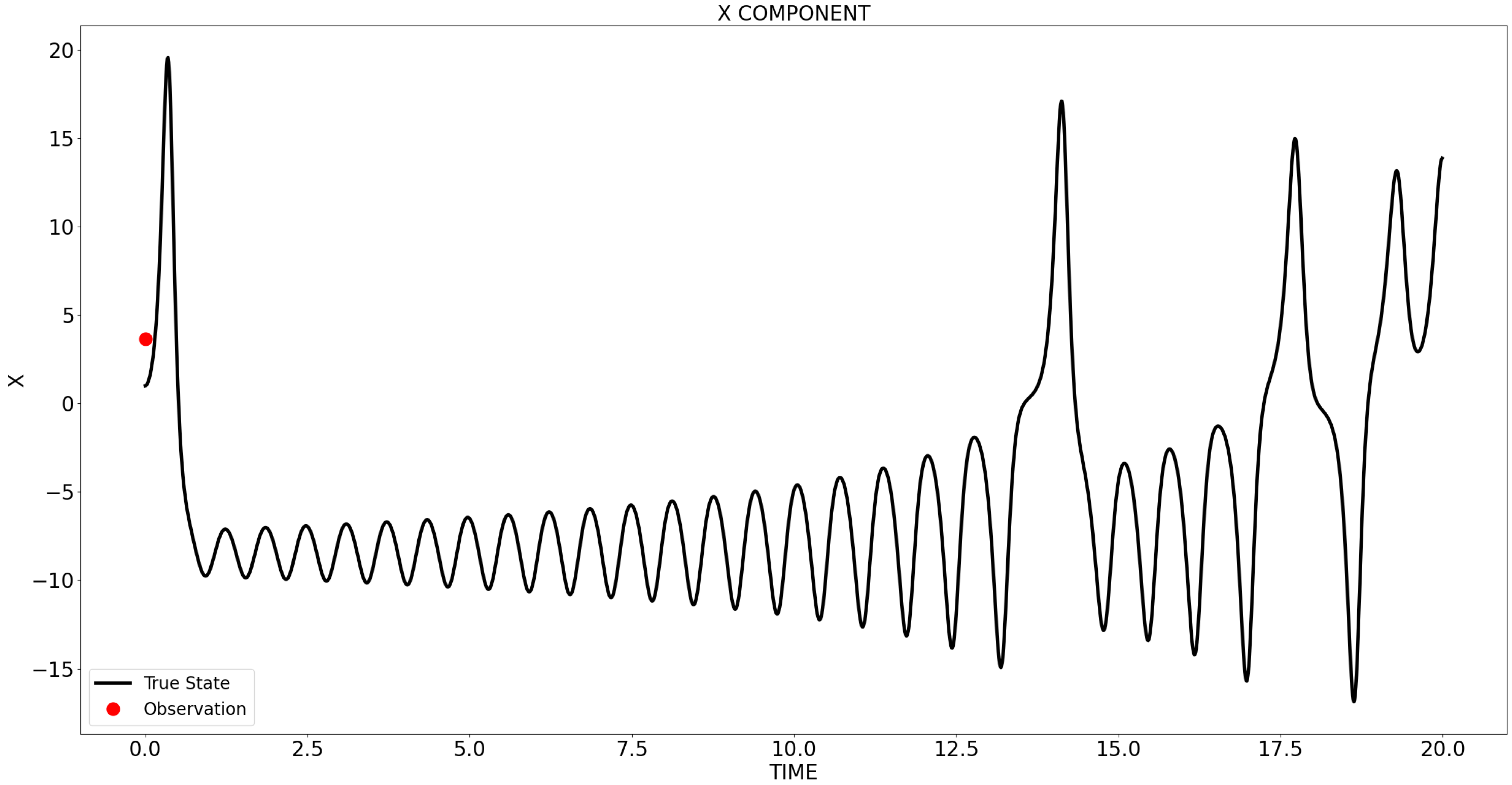

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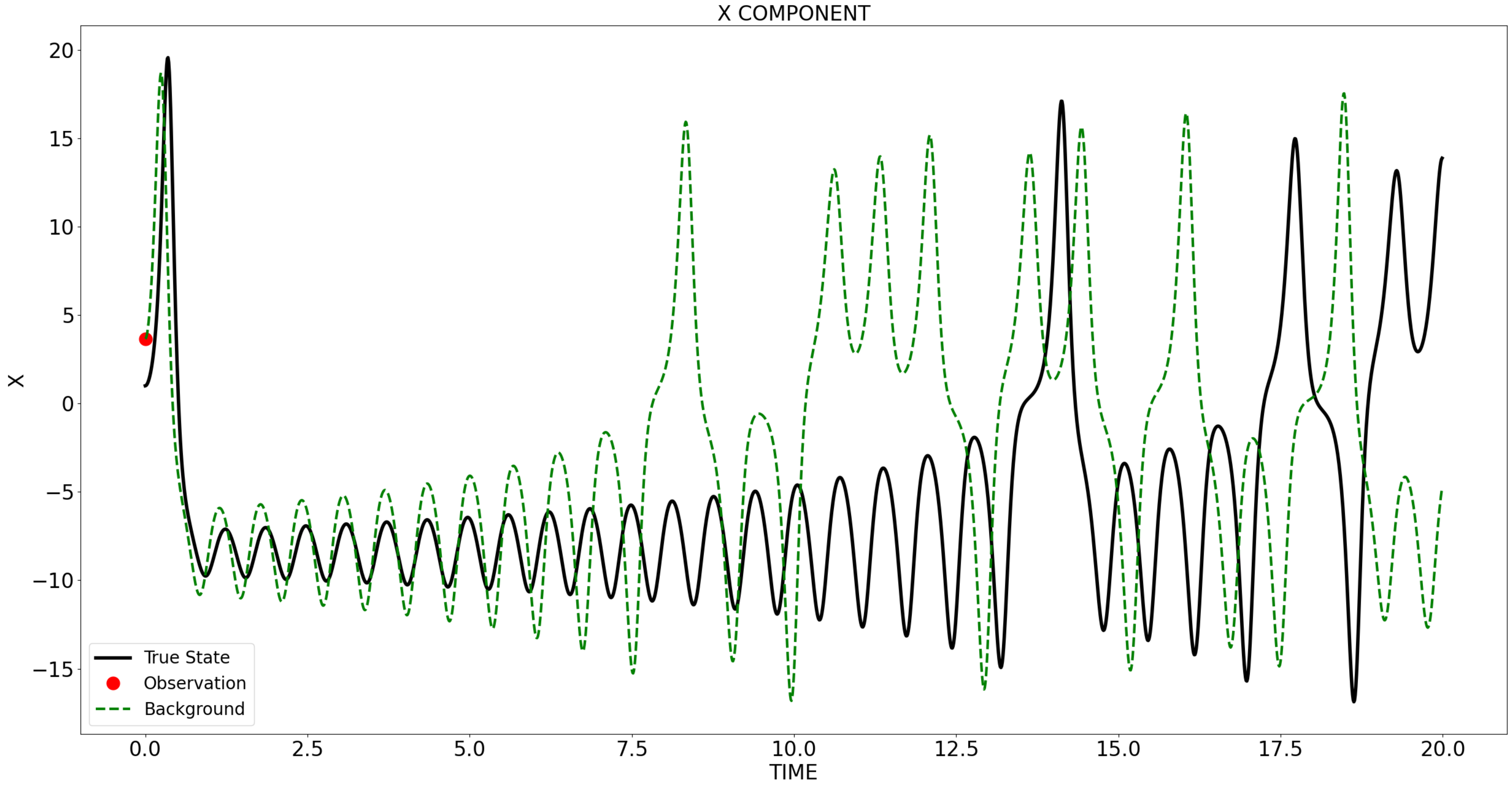

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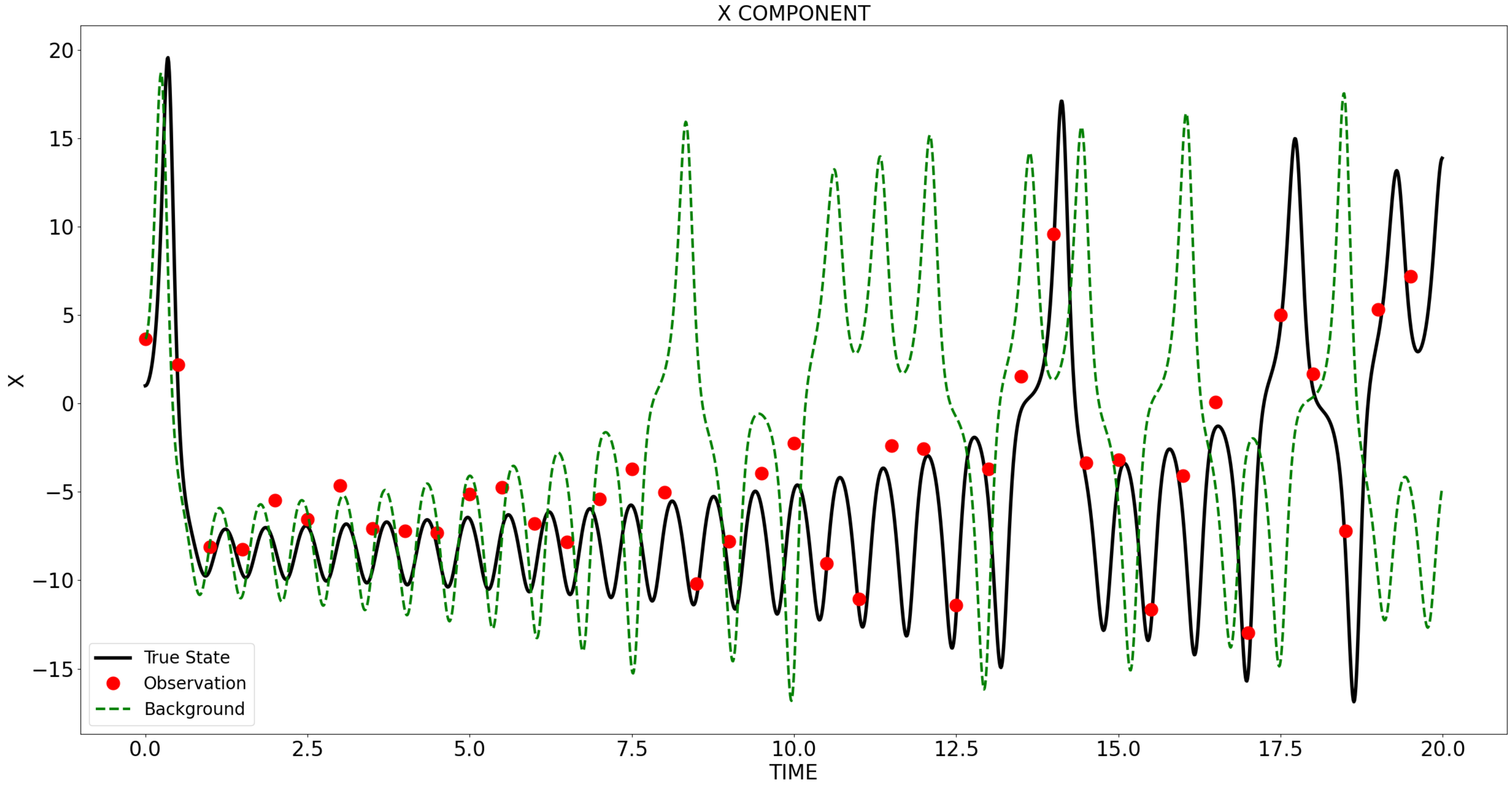

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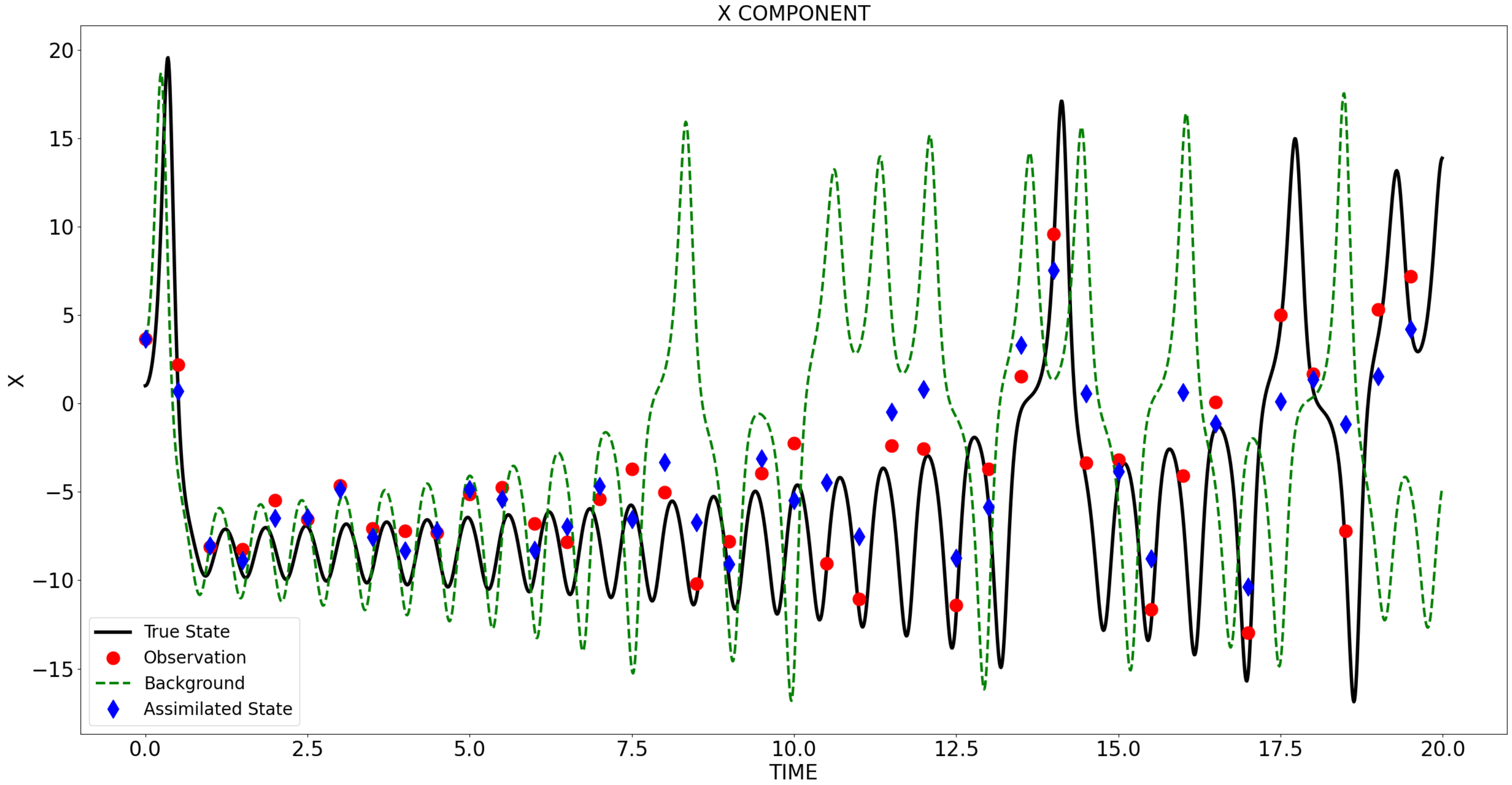

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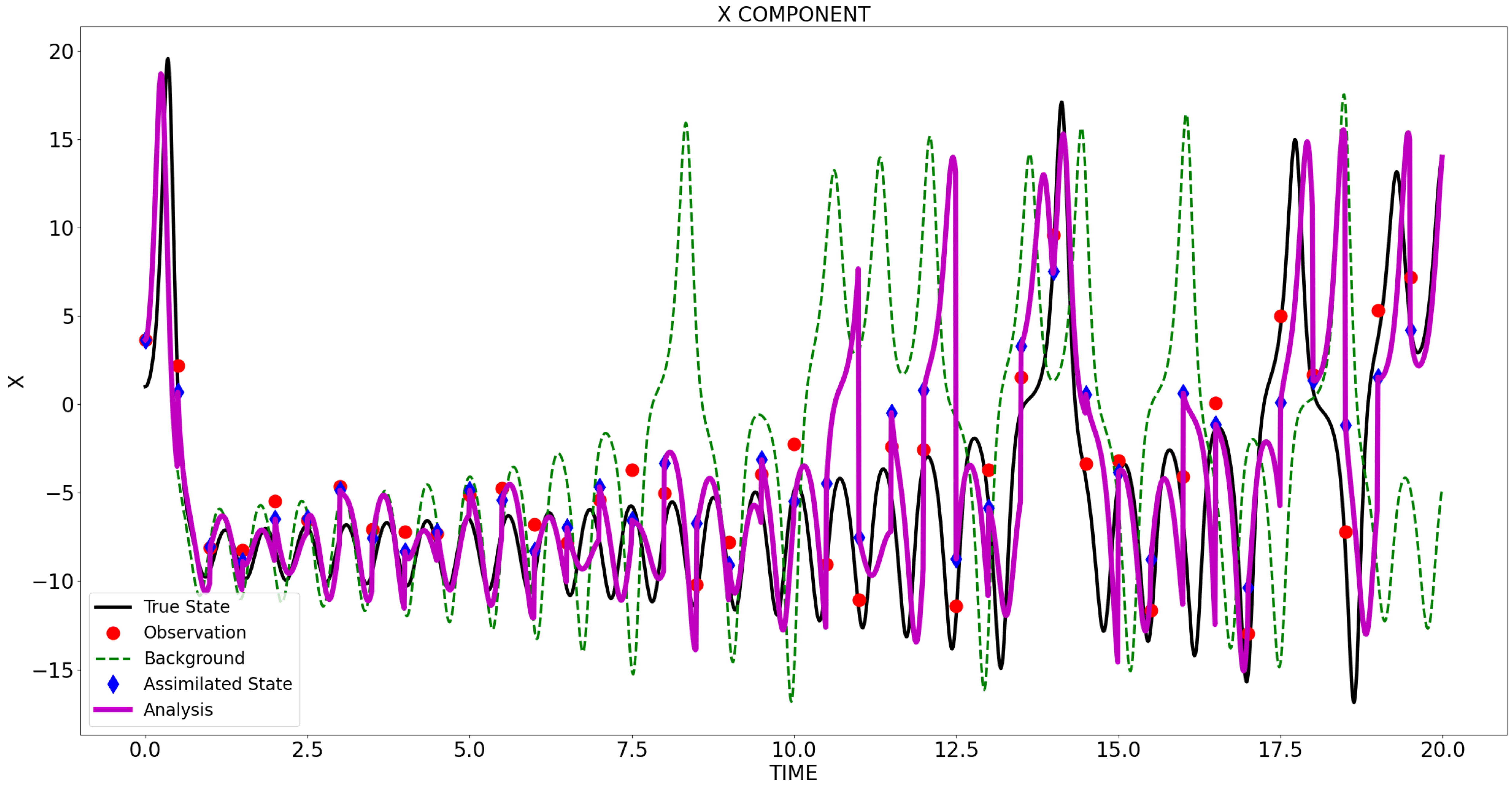
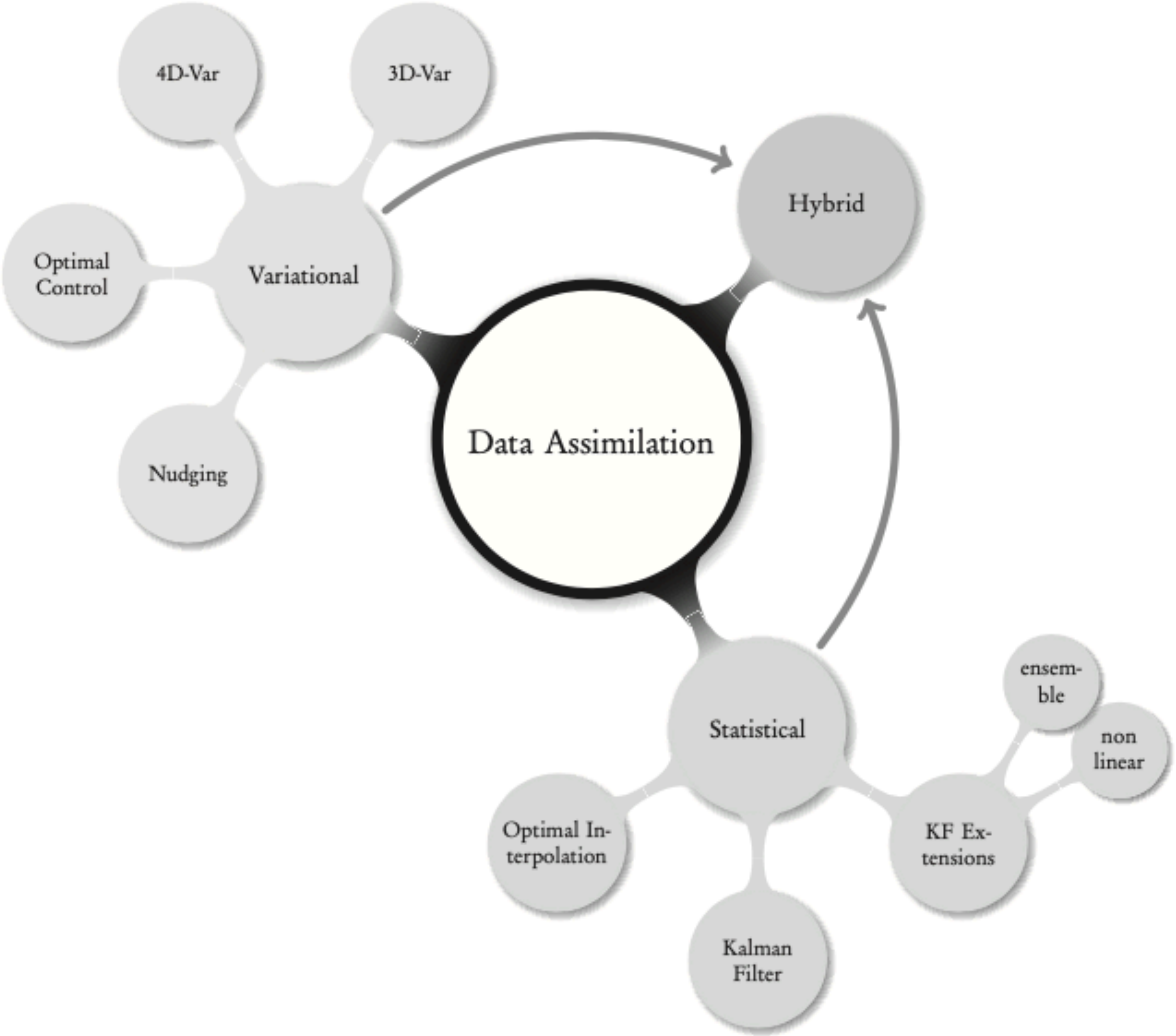


DIFFERENT METHODOLOGIES OF DATA ASSIMILATION



Data assimilation, methods and applications. Ash et al. 2016

DATA ASSIMILATION
THE 3D-Var COST FUNCTION IN THE PHYSICAL SPACE

MODEL TERM | **OBSERVATIONAL TERM**

$$\mathcal{J}(\mathbf{x}) = \underbrace{\frac{1}{2}(\mathbf{x}-\mathbf{x}_\mathrm{b})^\mathrm{T}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_\mathrm{b})}_{\text{MODEL TERM}} + \underbrace{\frac{1}{2}(\mathbf{y}_\mathrm{o}-\mathcal{H}(\mathbf{x}))^\mathrm{T}\mathbf{R}^{-1}(\mathbf{y}_\mathrm{o}-\mathcal{H}(\mathbf{x}))}_{\text{OBSERVATIONAL TERM}}$$

State vector
$\mathbf{x} \rightarrow \mathcal{O}(10^6)$

Background state vector
$\mathbf{x}_b \rightarrow \mathcal{O}(10^6)$

Background error covariance matrix
$\mathbf{B} \rightarrow \mathcal{O}(10^{12})$
↓
LINEAR
In operative systems

Observation vector

Observational error covariance matrix

NON-LINEAR **observation operator**
↓
LINEAR
In operative systems
$\mathbf{H}$

WHY WE WANT TO ASSIMILATE RADAR DATA?

Assimilating radar data is still a challenging task. WHY?

- They represent a quantity (reflectivity) with no direct functional correspondence to prognostic model variables (e.g. T, q, $\mathbf{v}$). [1]

- Convective storms have considerably more small-scale variability than other fields. [1]

$$\mathcal{J}(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_\mathrm{b})^\mathrm{T}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_\mathrm{b}) + \frac{1}{2}(\mathbf{y}_\mathrm{o} - \mathcal{H}(\mathbf{x}))^\mathrm{T}\mathbf{R}^{-1}(\mathbf{y}_\mathrm{o} - \mathcal{H}(\mathbf{x}))$$

Reflectivity (t, z)

$[T(t,z), u(t,z), v(t,z), q(t,z), p(t,z=0)]$

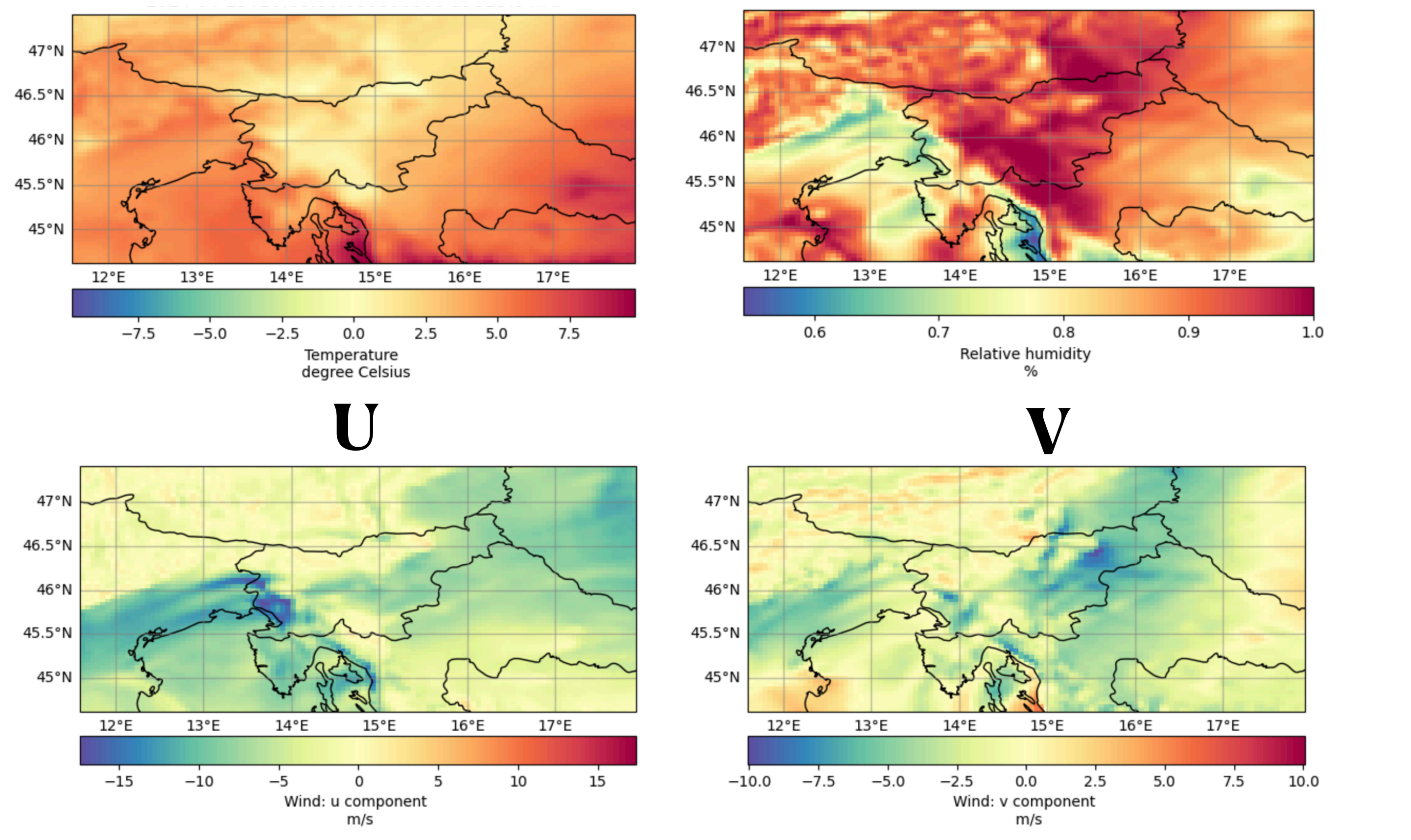
PROJECT METHODOLOGY

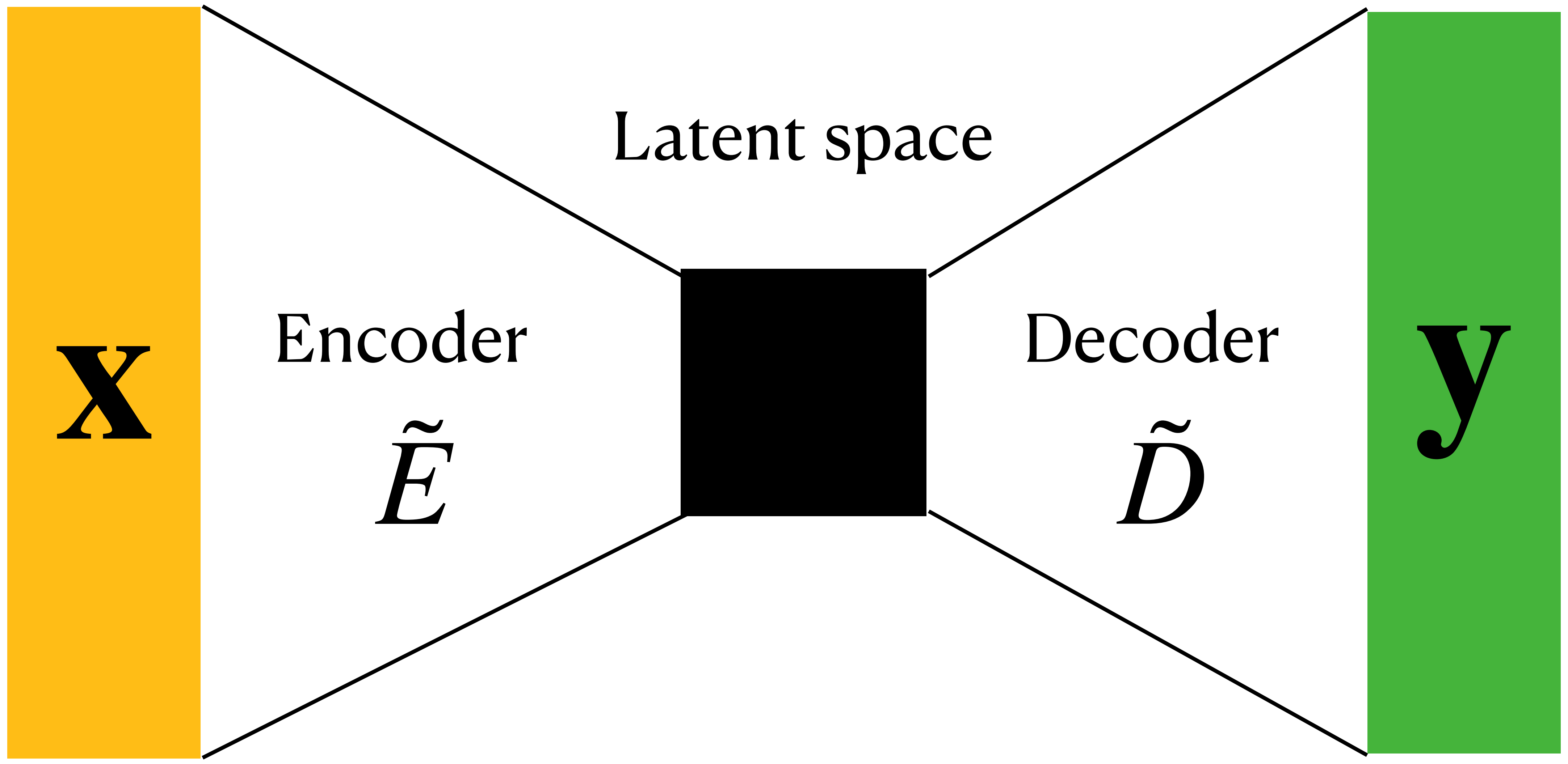
Build an encoder-decoder neural network with **input model data** and **output reflectivity data.**

ALADIN MODEL VARIABLES

TEMPERATURE **RELATIVE HUMIDITY**

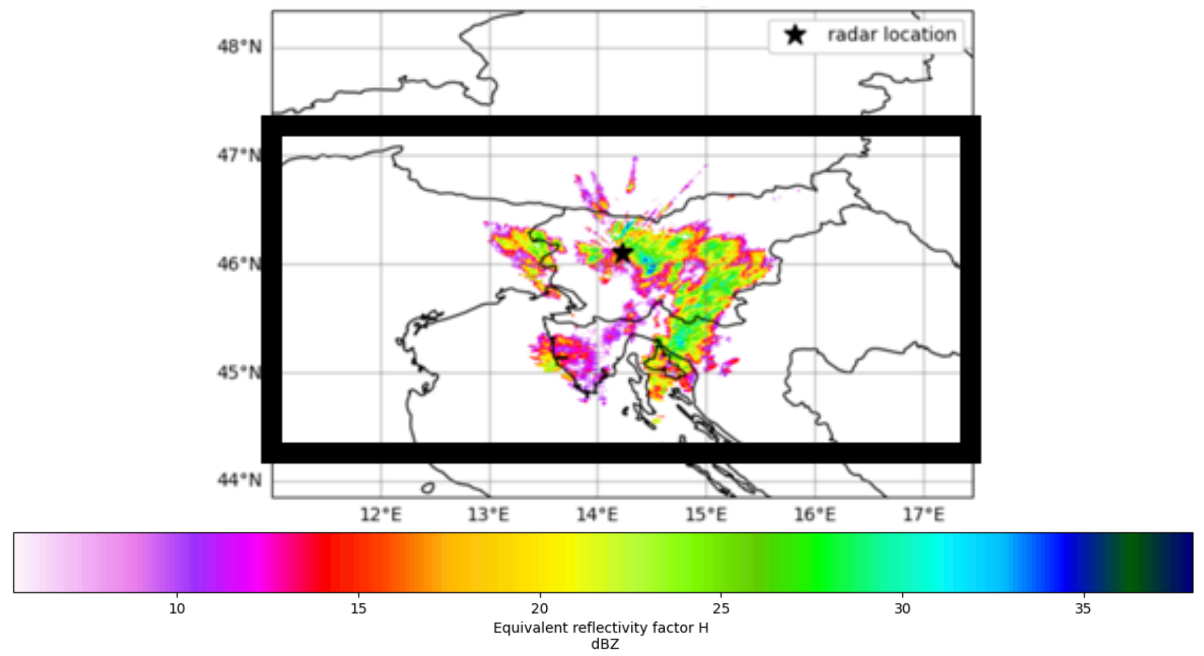
U **V**





RADAR OBSERVATIONS

RADIANCE



$$\mathbf{y}' = \tilde{D}(\tilde{E}(\mathbf{x})) = \mathscr{H}(\mathbf{x})$$

↓ Generated Model-Equivalent radar reflectivities

↓ Non-linear Observation Operator

RESULTS APPLICATIONS

PHYSICAL SPACE — OBSERVATION SPACE

$$\mathcal{J}(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + \frac{1}{2}(\mathbf{y}_o - \mathbf{H}(\mathbf{x}))^T\mathbf{R}^{-1}(\mathbf{y}_o - \mathbf{H}(\mathbf{x}))$$

Physical space 3D-Var cost function

$$\mathcal{H}(\mathbf{x}) = \tilde{D}(\tilde{E}(\mathbf{x}))$$

$$\mathcal{J}(\mathbf{z}) = \frac{1}{2}(\mathbf{z}-\mathbf{z}_b)^T\mathbf{B}_z^{-1}(\mathbf{z}-\mathbf{z}_b) + \frac{1}{2}(\mathbf{y}_o - \mathbf{H}[\mathbf{D}(\mathbf{z})])^T\mathbf{R}^{-1}(\mathbf{y}_o - \mathbf{H}[\mathbf{D}(\mathbf{z})])$$

LATENT SPACE — OBSERVATION SPACE

Latent space 3D-Var cost function

Melnic and Zaplotnic; Neural-Network Data Assimilation using Variational Autoencoder. (2023)

ADDED VALUE OF TH E PROJECT

Definition of a non-linear observation operator to assimilate radar data and a possible improvement of the NWP skill in forecasting CONVECTIVE STORMS

HEAVY PRECIPITATIONS IN THE CLIMATE CHANGE ERA: MORE FREQUENT & MORE INTENSE

'Nature fights back': Slovenia's worst floods kill six

By **Fedja Grulovic**

August 7, 2023 3:44 PM GMT+2 · Updated a year ago

Aa

[5/5] A view of a damaged building in a flooded area, following heavy rains, in Prevalje, Slovenia August 6, 2023. REUTERS/Fedja Grulovic/File photo Purchase Licensing Rights

Flash floods and landslides hit parts of Bosnia, killing at least 16

Friday 4 October 2024 16:35, UK

Search and rescue teams look for people in the flooded houses in Jablanica, Bosnia. Pic: AP

CLIMATE

Catastrophic floods in Italy force thousands of people to leave their homes

PUBLISHED THU, MAY 18 2023•1:19 PM EDT

In this aerial picture, flooded streets caused by heavy rains across Italy's northern Emilia Romagna region, on May 18, 2023 in Lugo, Italy.

Antonio Masiello | Getty Images

Thank you!

Marco Stefanelli

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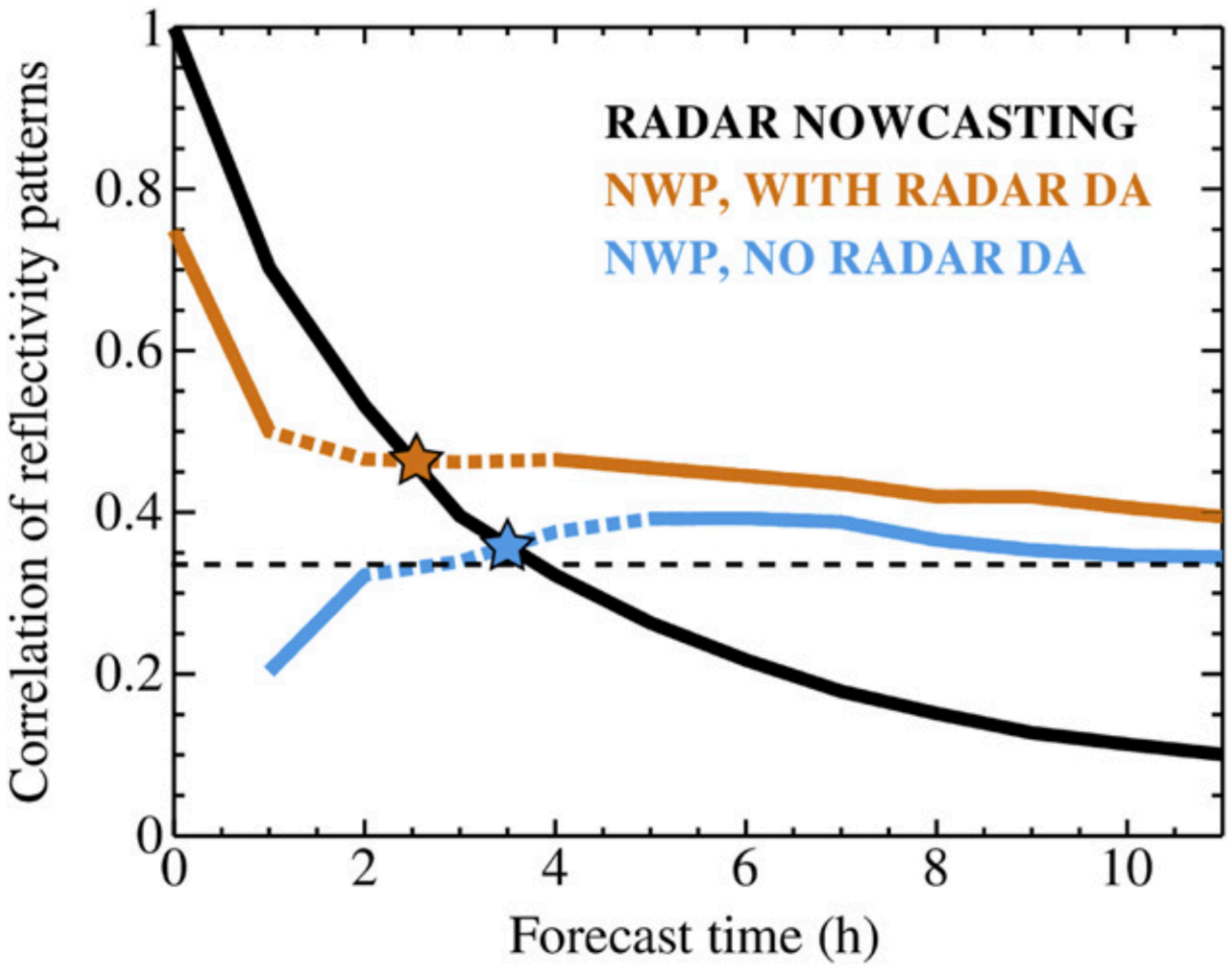
SMASH

WHY WE WANT TO ASSIMILATE RADAR DATA?

RADAR IS OUR BEST INSTRUMENT TO MONITOR AND STUDY STORMS

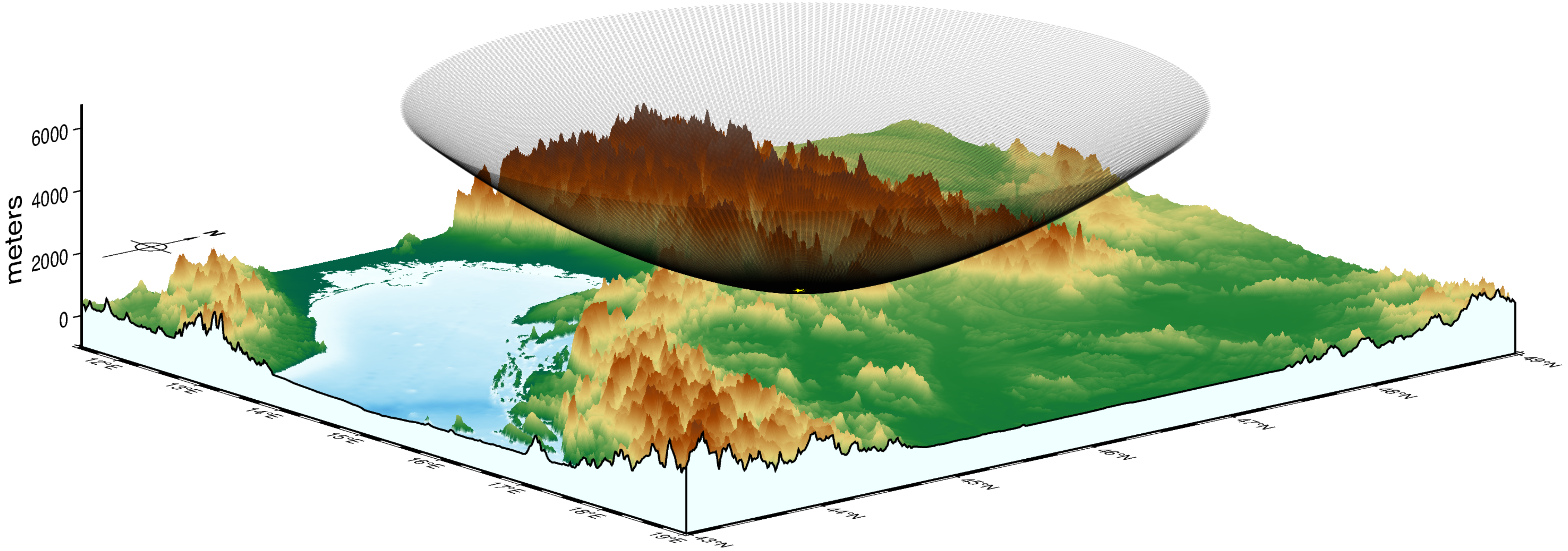
Attempts to assimilate radar data showed poor improvements in forecasting precipitation patterns.

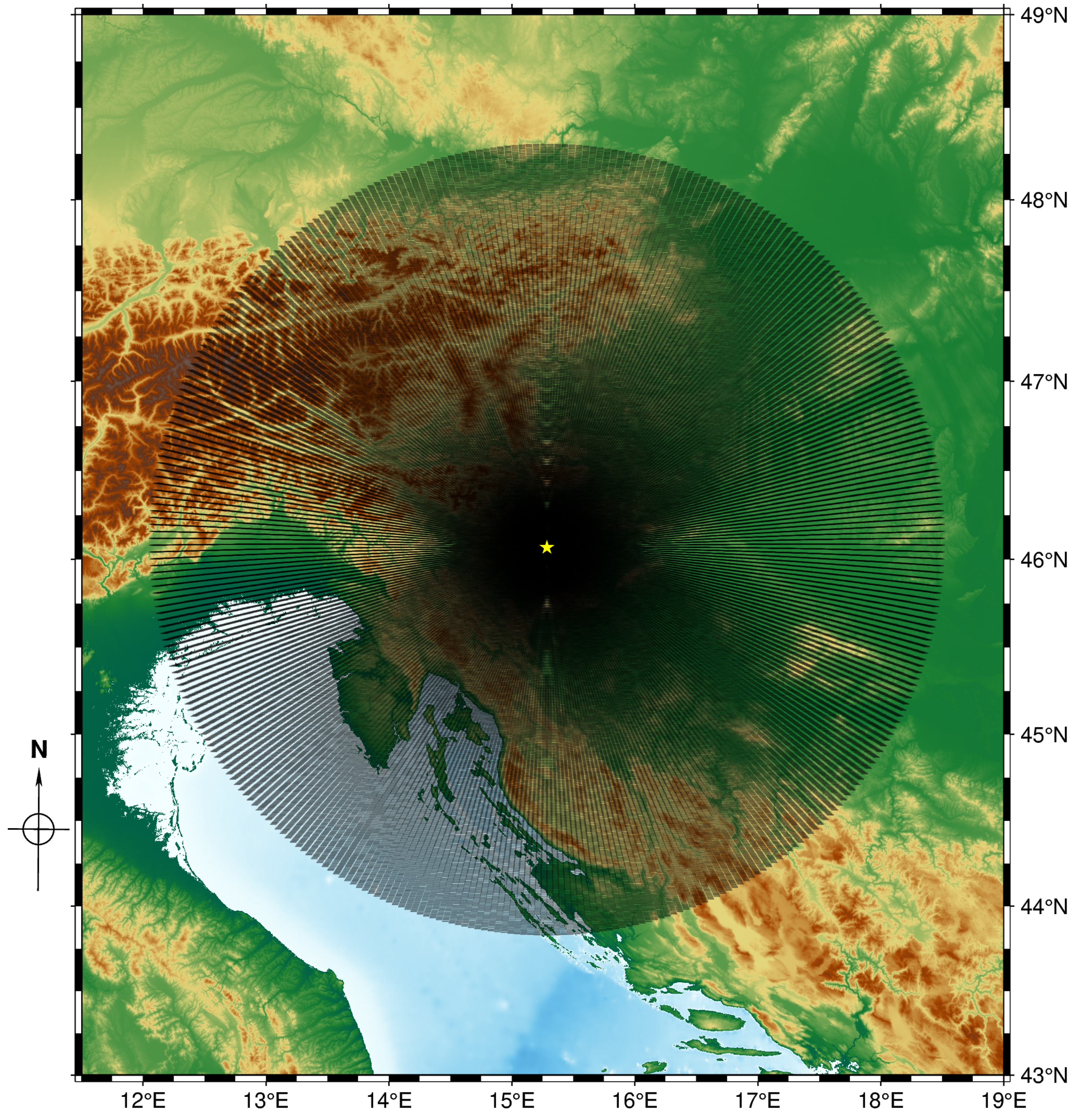


- Skill of NWP aided by radar data assimilation drops very rapidly in the first forecast hour
- Extrapolation methods (NOWCASTING) beat numerical forecasting of precipitation patterns in the first 2 or 3 h

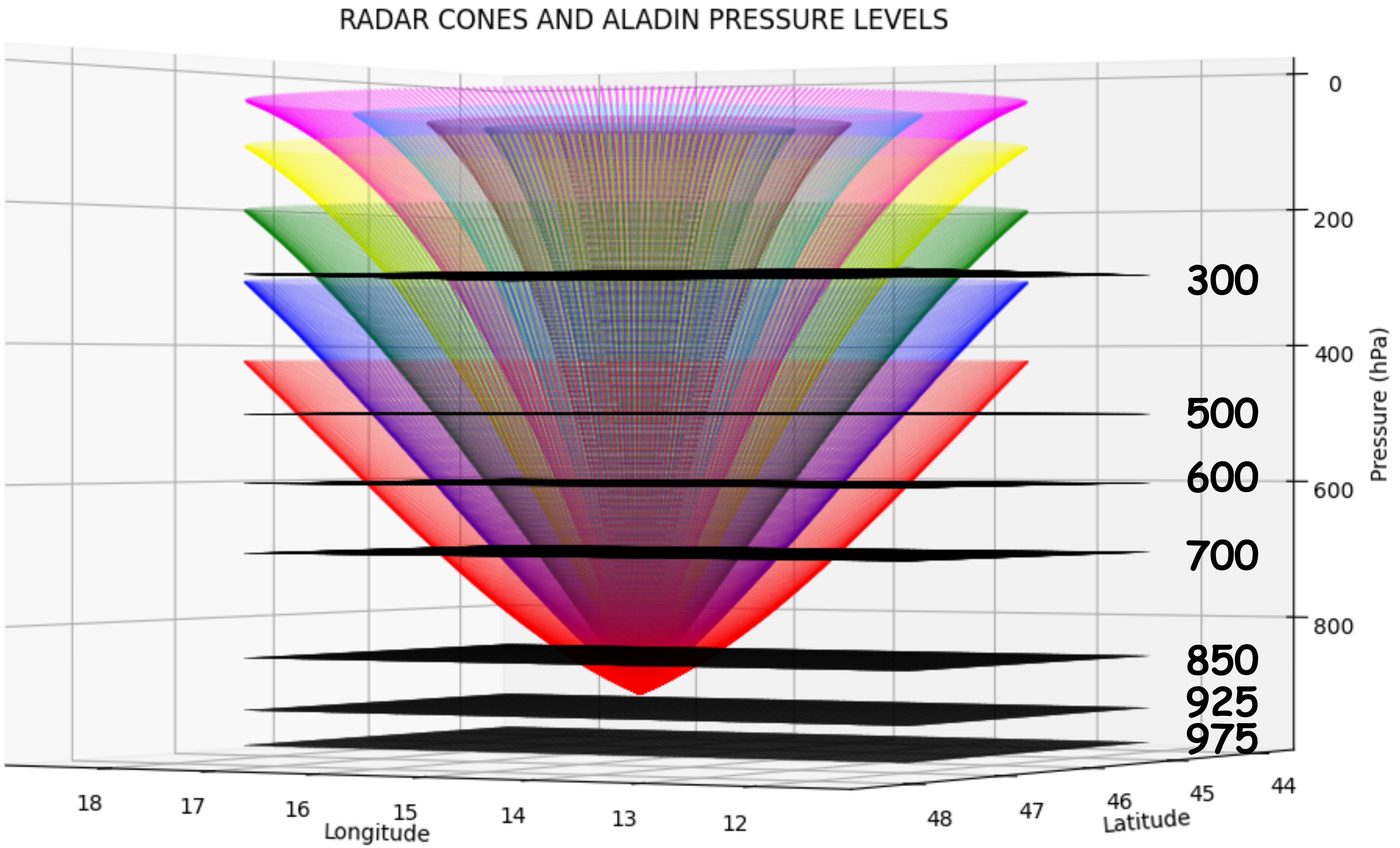
Fabry, F., & Meunier, V. (2020). Why are radar data so difficult to assimilate skillfully? Monthly Weather Review, 148(7), 2819-2836.

RADAR DATA STRUCTURE OF THE FIRST ELEVATION ANGLE 0.5 deg





ALADIN PRESSURE LEVELS AND RADAR DATA AT DIFFERENT ELEVATION ANGLES



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