How rich metadata schemes can allow for better designs via optimization under uncertainty

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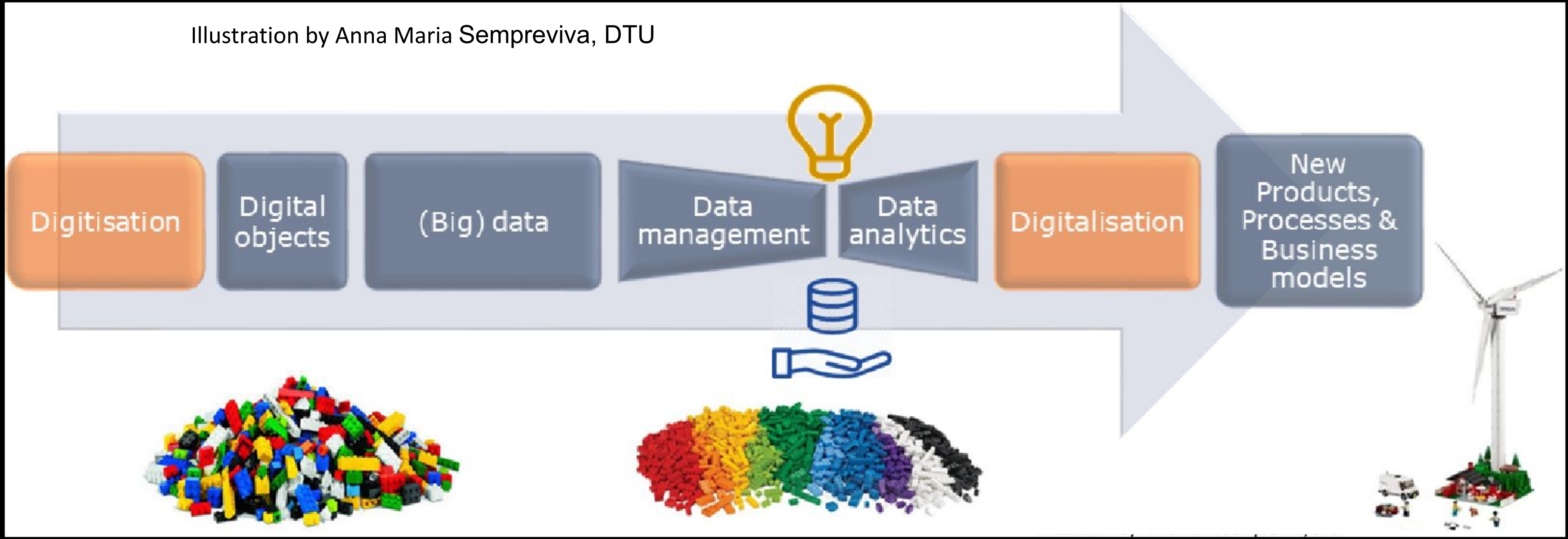
DTU

WIND ENERGY DIGITALIZATION
IEA WIND TASK 43

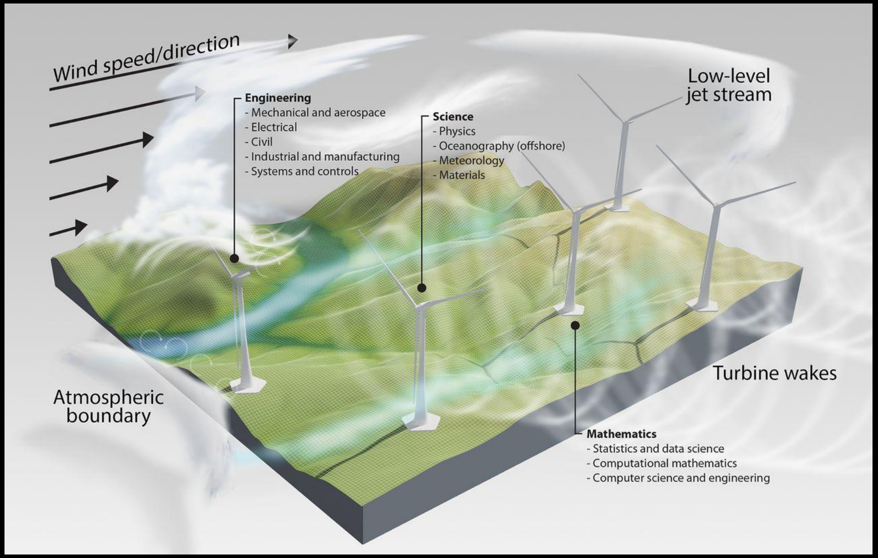
Motivation



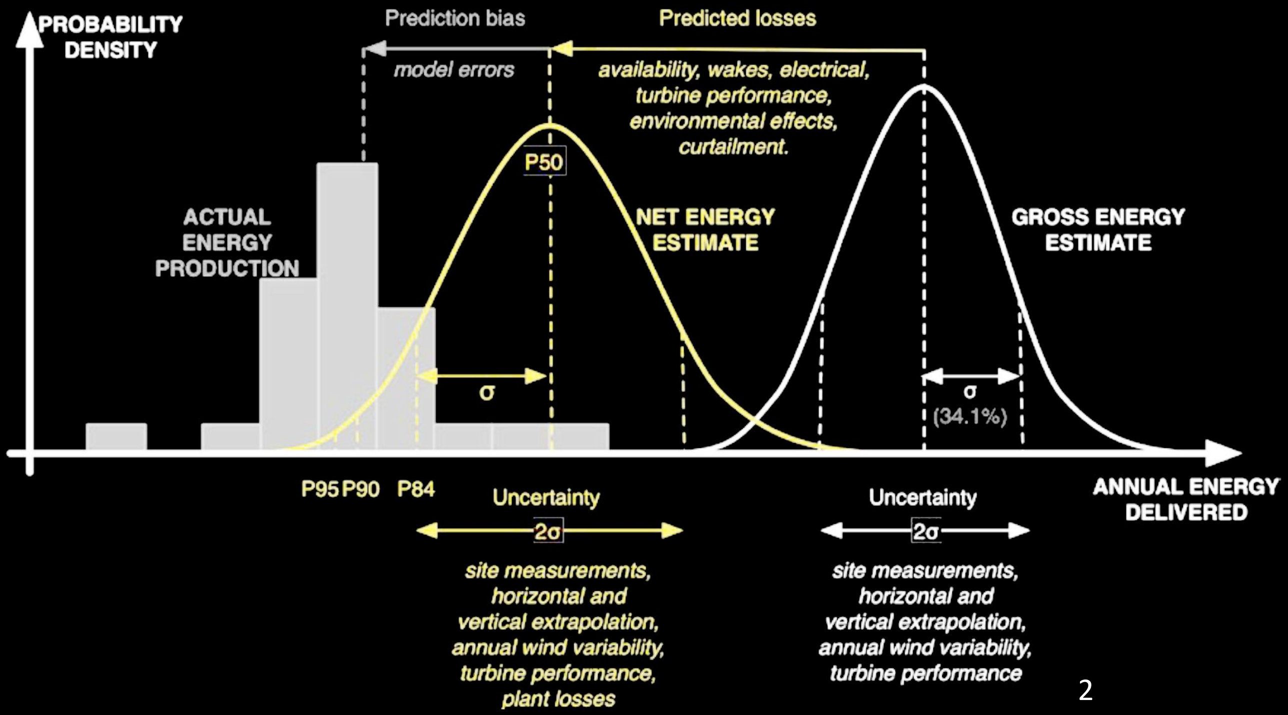
- Data is the lifeblood of artificial intelligence and analytics
- Metadata (data about data) provides valuable contextual information, including information about uncertainty (what we know and don't know)
- Data/metadata management is a deliberate buisness strategy, often requiring schema, taxonomies, or ontologies for successful knowledge integration
- Deliberate management of uncertainty information enables optimization under uncertainty, where a product is designed to anticipate gaps in information

Need for Quantifying Uncertainty

- Wind energy systems have limited information available when predicting complex phenomena
- Stochastic forcing due to atmospheric turbulence
- Challenging to forecast future behavior
- Business decisions rely on model forecasts
- Understanding risk can give a competitive edge



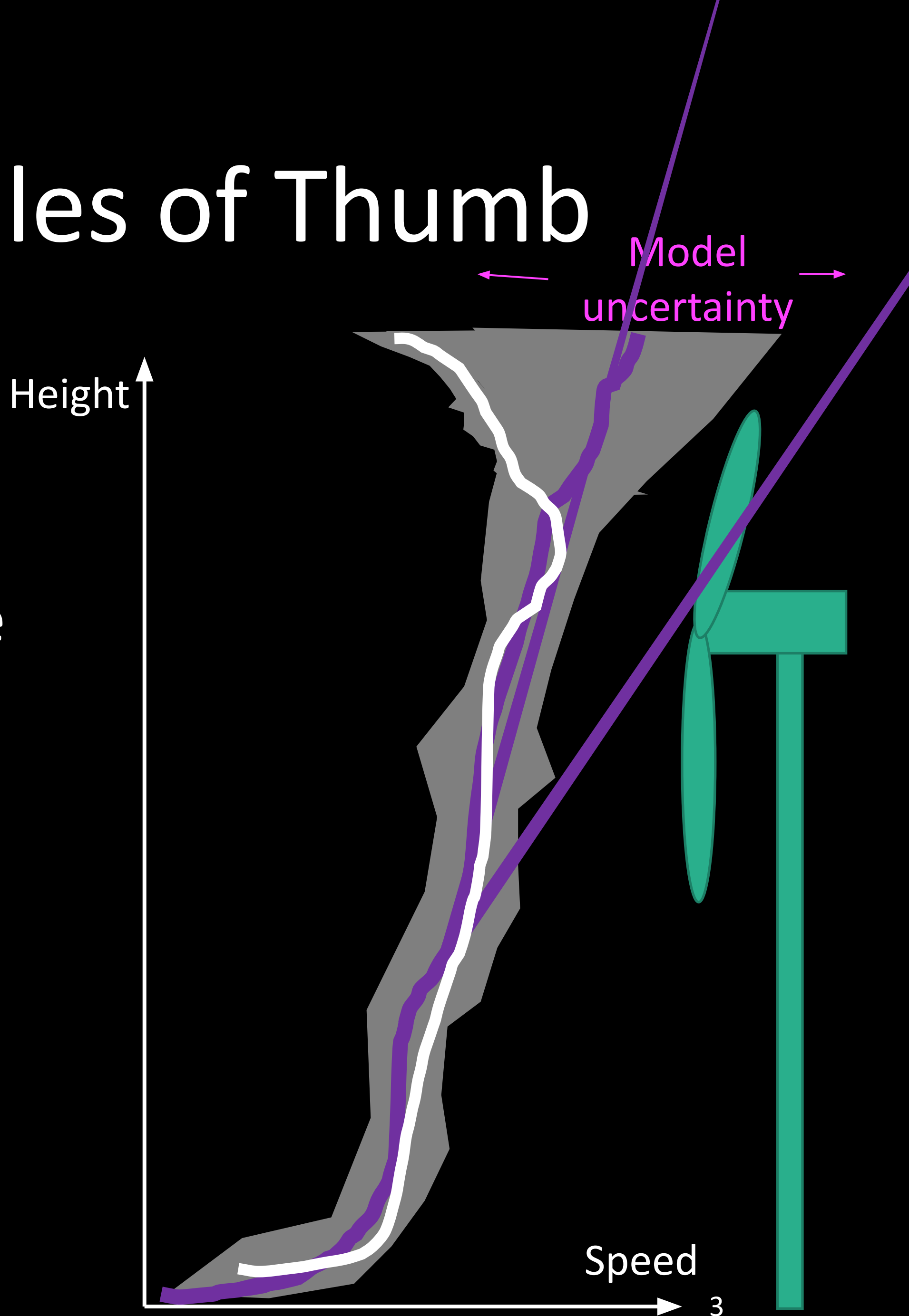
Veers *et al.*, “Grand challenges in the science of wind energy“ Science 366.6464 (2019)



Clifton, Andrew, Aaron Smith, and Michael Fields. *Wind plant preconstruction energy estimates. current practice and opportunities*. No. NREL/TP-5000-64735, 2016

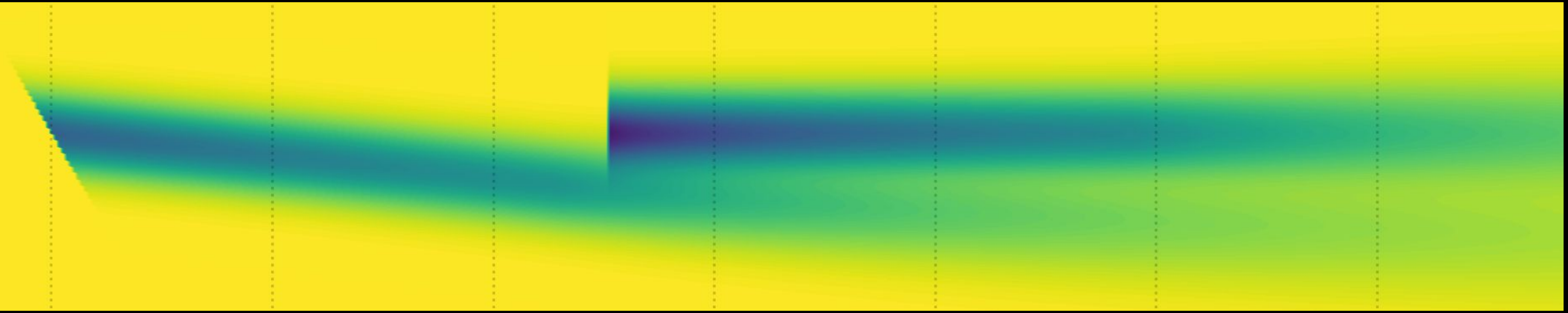
Uncertainty Quantification Rules of Thumb

- Uncertainty should be reduced by adding new perfect measurements
- Reducing measurement uncertainty should reduce uncertainty
- Avoid assuming a model to be reality, but have a Bayesian approach based on experiments, measurements, and expert knowledge



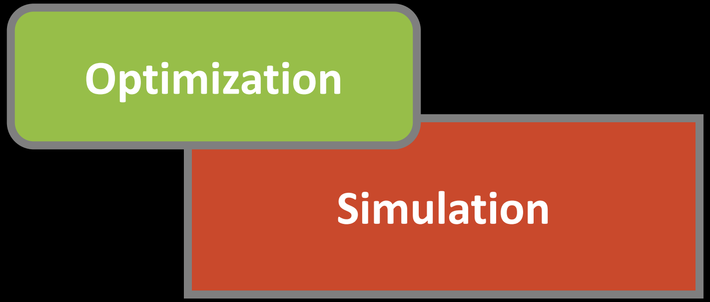
Wake Steering OUU Example

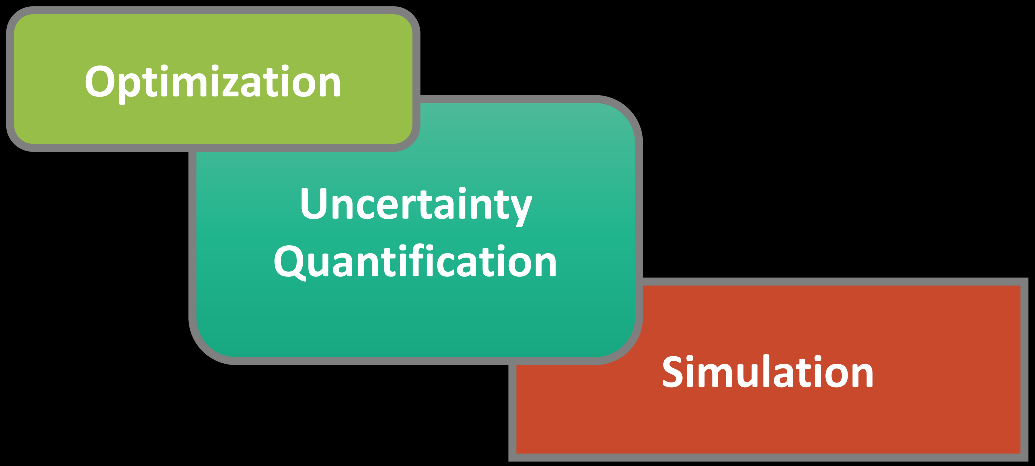
- Upstream turbines redirect yaw orientation away from incoming wind, “steering” the wake away from downstream turbines
- I explored the impacts of designing wake steering strategies around uncertainty
  - Quantify sensitivity of design to different uncertainties
  - Quantify expected gains in energy from OUU



Optimization Under Uncertainty (OUU)

- We explored the impacts of designing wake steering strategies around uncertainty
  - Quantify sensitivity of design to different uncertainties
  - Quantify expected gains in energy from OUU
- FLORIS engineering wake model is employed



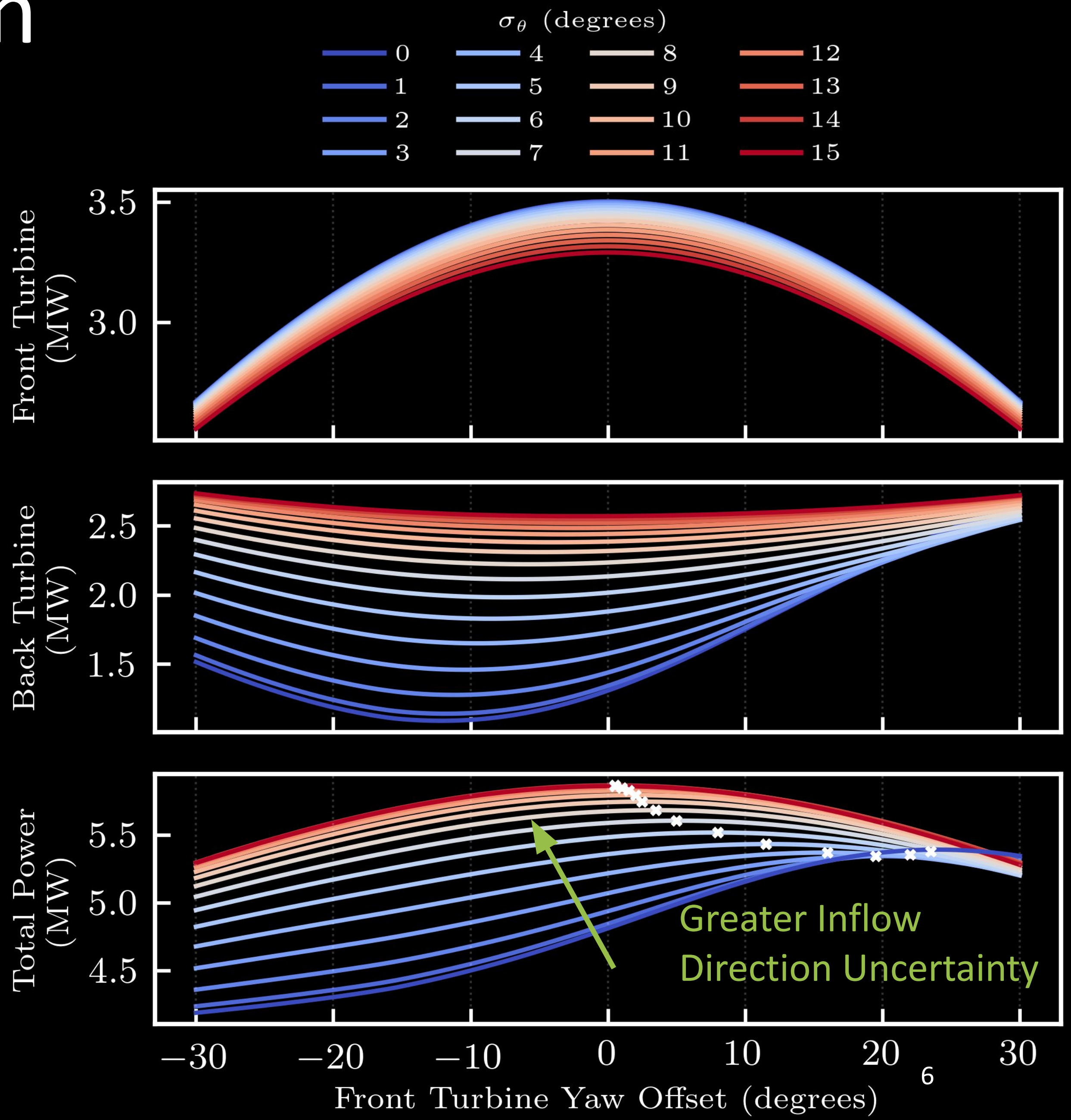


Uncertainty Impacts Design

- Direction and speed uncertainty were determined to be most influential uncertainties
- Uncertainty in direction smears wake

$$\frac{\text{Stochastic OUU Power}}{\text{Stochastic det. Power}} - 1$$

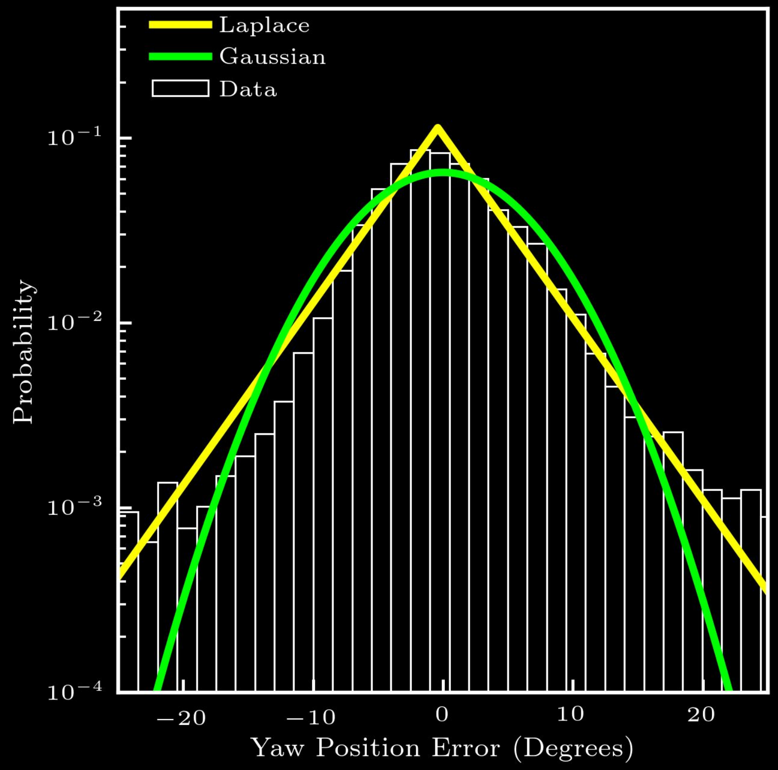
Parameter	max(VSS) (%)
Inflow Direction	**5.40**
Inflow Speed	**0.60**
Yaw Position	0.32
Turbulence Intensity	0.28
Shear	0.02



Leaning Uncertainty as Metadata

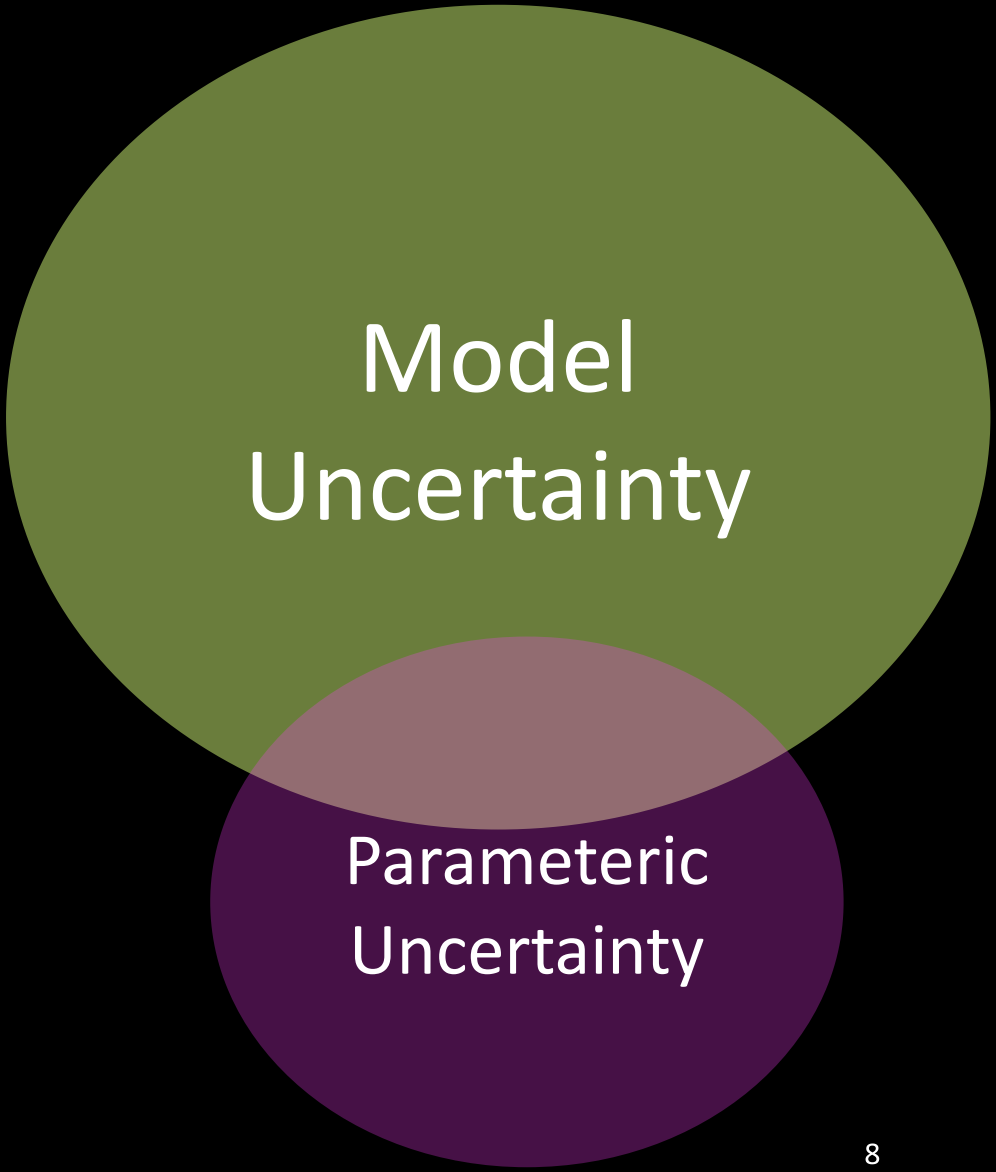
- Reasonable input probability distributions were developed for yaw offsets, incoming wind direction, wind speed, turbulence intensity, and shear, to be representative over a ten-minute period
- From experimental data, the distribution of yaw errors appears to follow a Laplace distribution

Parameter	Distribution	Hyperparameter



Confronting Model Form Uncertainty

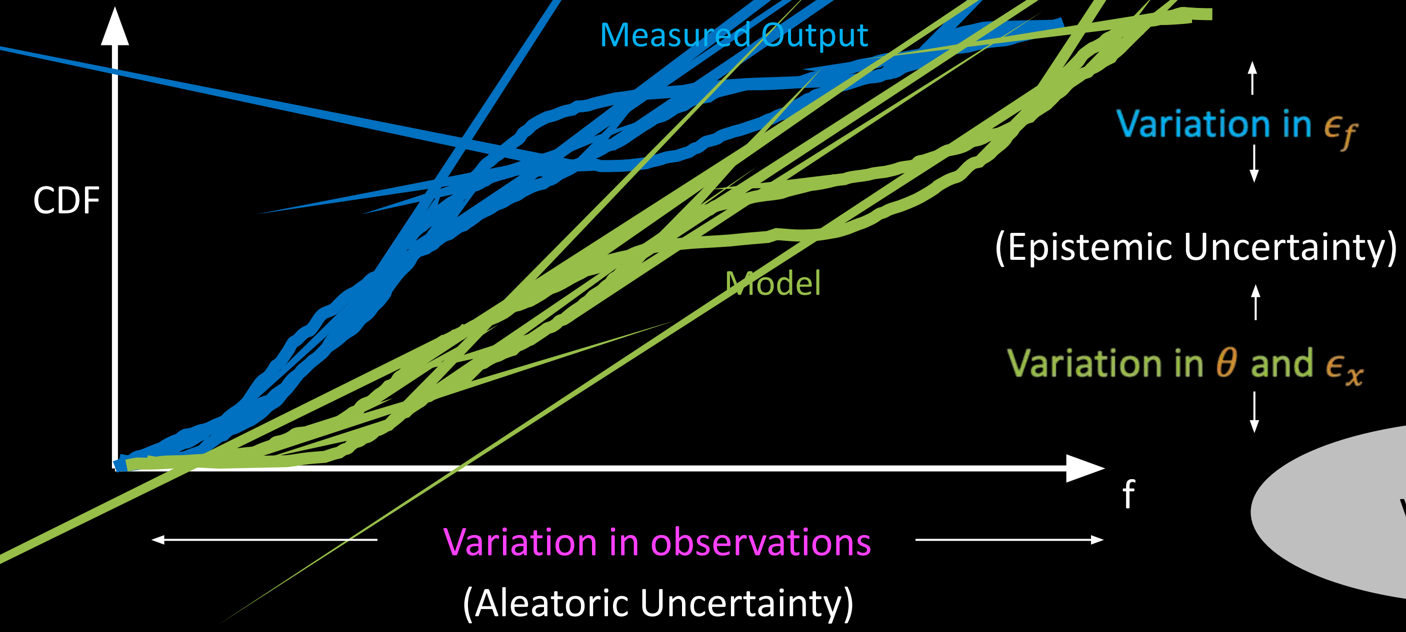
- Goal of uncertainty quantification is to understand how well the range of experiment outcome, $f(x)$, is predicted by a computer model, $\mathrm{m}(x, \theta)$
- Uncertainty distributions must be assigned to inputs
- The model form and choice of parameters have been carefully chosen—the same knowledge should be used to form the uncertainty paramerization

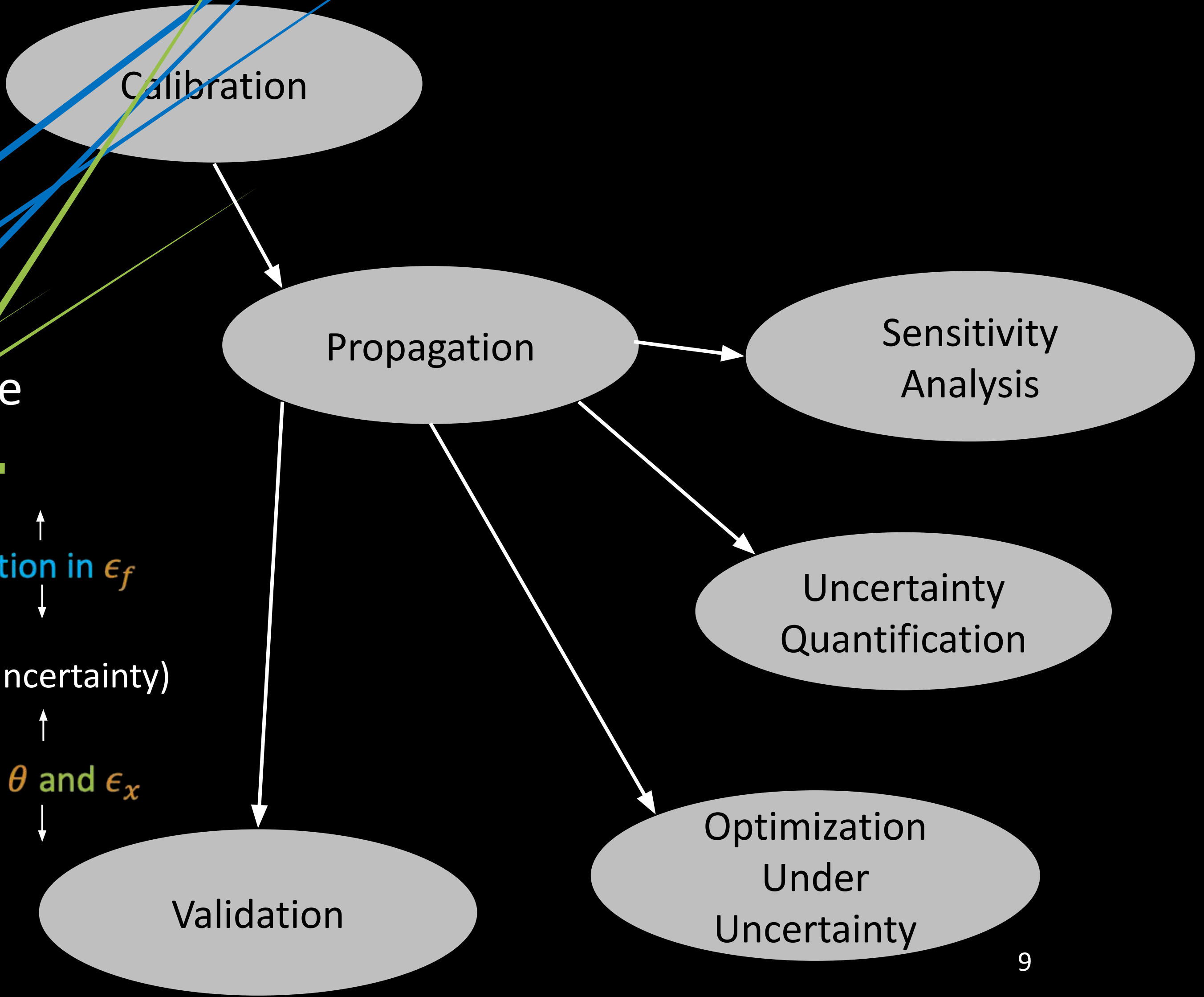


Managing Uncertainty

Model → $m(x + \epsilon_x, \theta) + \epsilon_m = \hat{f}(x) + \epsilon_f$ ← Measured Output

- Calibration and Validation allow for riggourous understandings of uncertainty by taking previous experience into account
- Epistemic Uncertainty
  - Reducable. Due to lack of knowledge
  - Examples: wake modeling, sensor errors
- Aleatoric Uncertainty
  - Irreducable, due to natural variability
  - Examples: atmospheric variation, turbulence





Schema

A schema is a "blueprint" of what data looks like. More formally, it's an expression of descriptive and structural metadata with defined semantics.

- Example: JSON File with predefined fields
- Allows for strategic data collection

Example Met Mast Schema

Measured Data

Time series of measurements at different heights

Obstructions

Core Metadata

- Data owner
- Met mast location

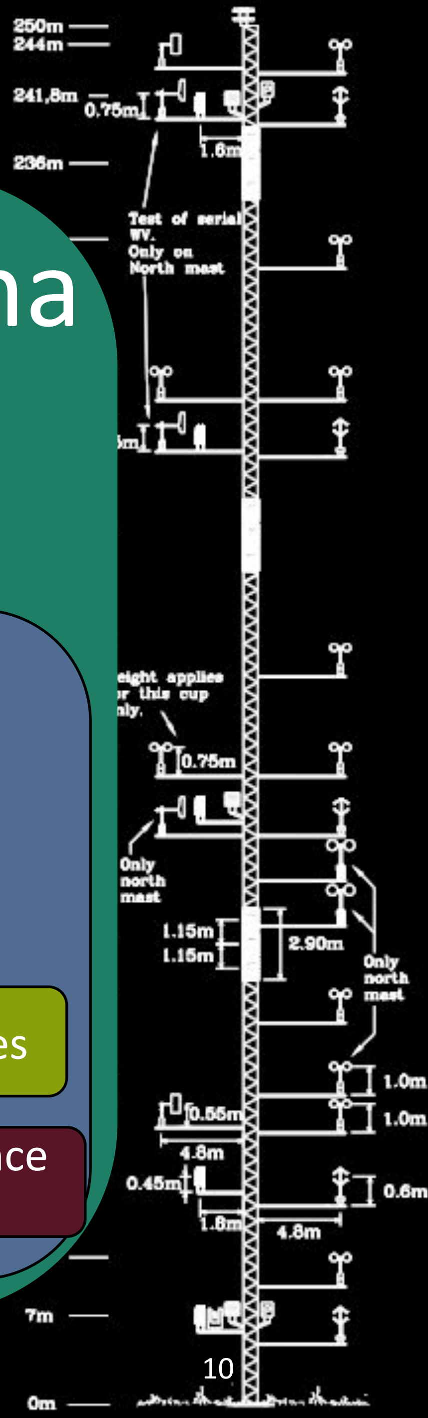
Instrument Metadata

- Heights
- Orientations
- Boom lengths
- Models, Manufacturer

Manufacturer specifications of measurement uncertainty

Warantees

Maintanance Schedule



Types of Metadata

Administrative

For managing data

- Project
- Resource owner
- Collaborators
- Funder
- Licence

Descriptive

Catalog information

- Keywords
- Topics
- Persistant Identifier
- Related resources
- Key performance indicators

Structural

Contextual information

- **Uncertainty**
- Assumptions
- Collection method
- Researcher notes

Form

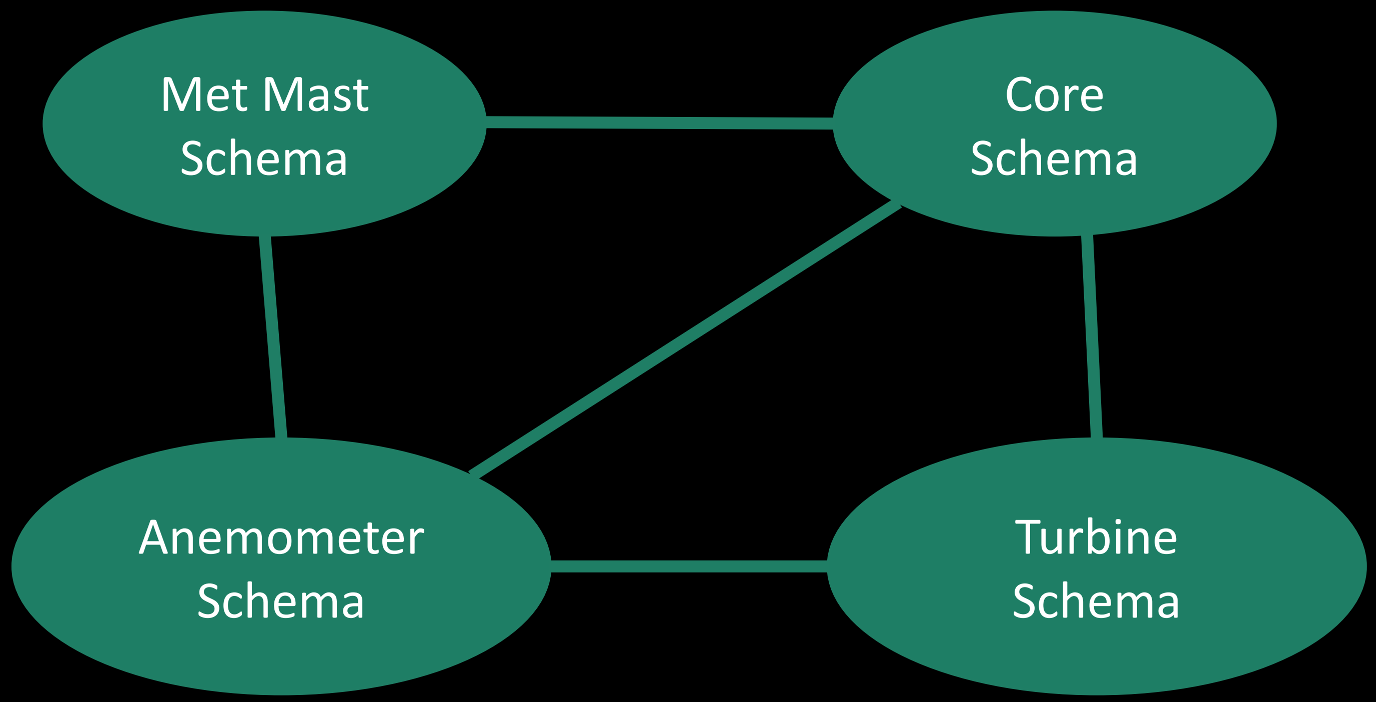
Internal data structure

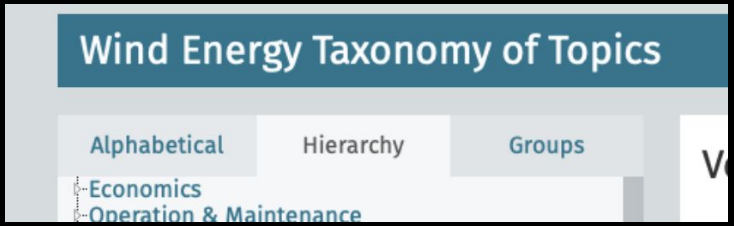
- Data size
- Data format
- Variable names and types

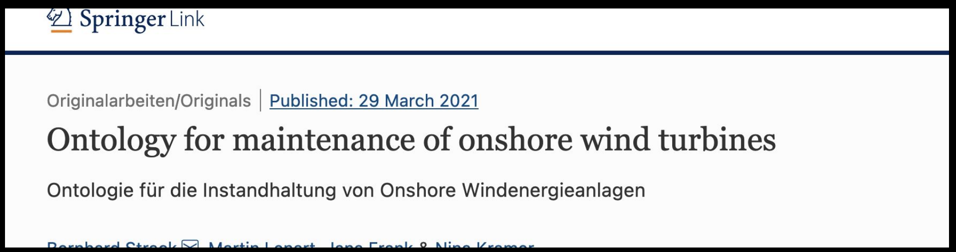
Ontology

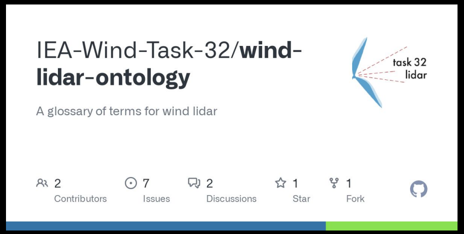
An ontology is an explicit specification of a conceptualization.

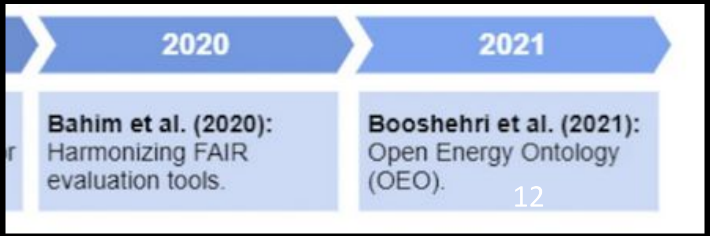
- Ontologist is a common job title in the tech sector
- Ontologies allow schema to be modular
- Relate concepts using logical operators:
  - subset (⊆) (taxonomy)
  - Equivalence (≡)
  - conjunction (∩)
  - disjunction (∪)
  - negation (¬)
  - property restrictions (∀, ∃)
  - tautology (⊤)
  - contradiction (⊥)





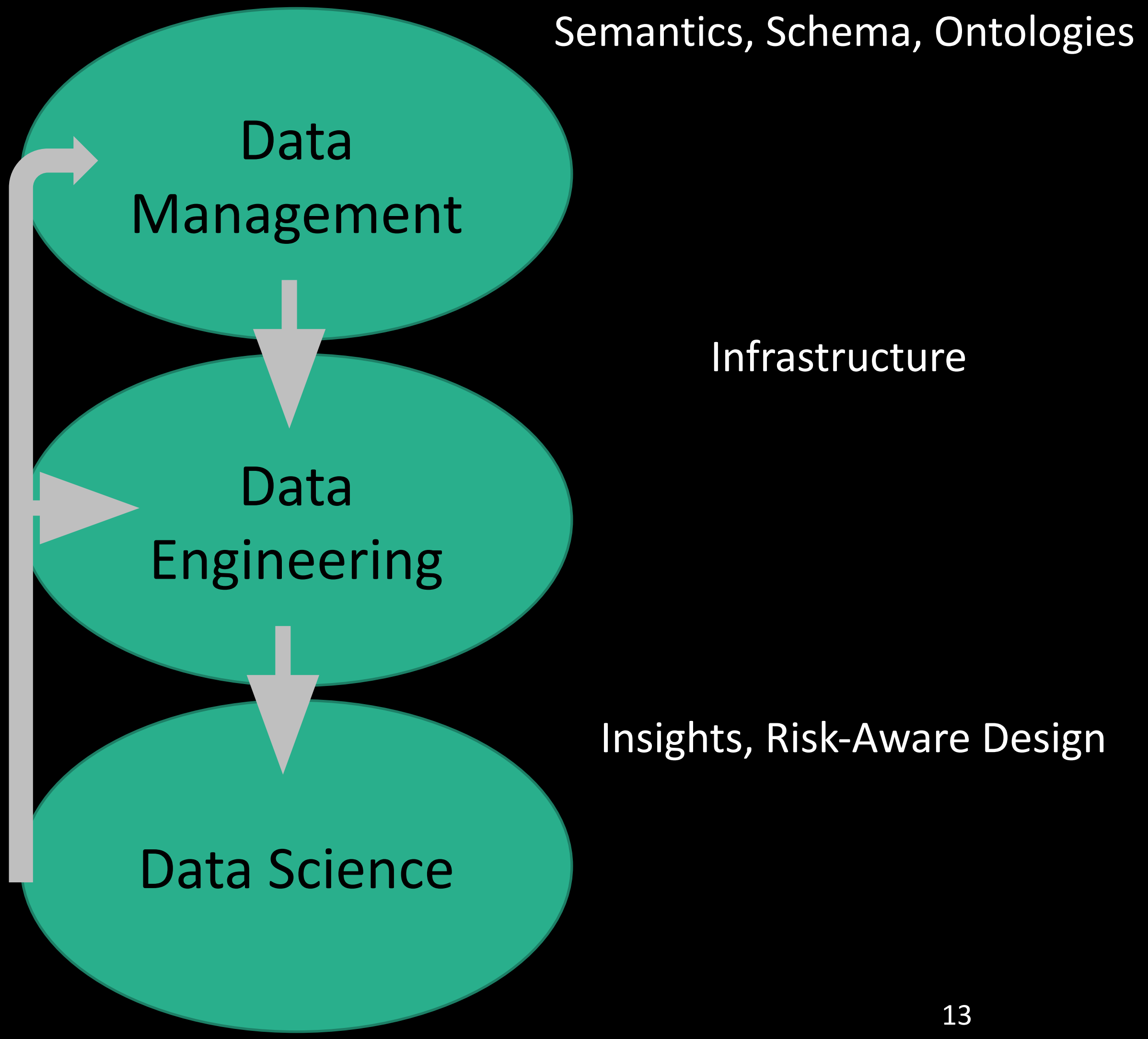




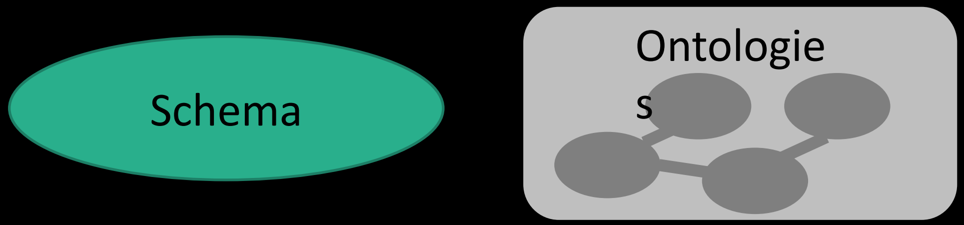


Invest in Metadata Infrastructure

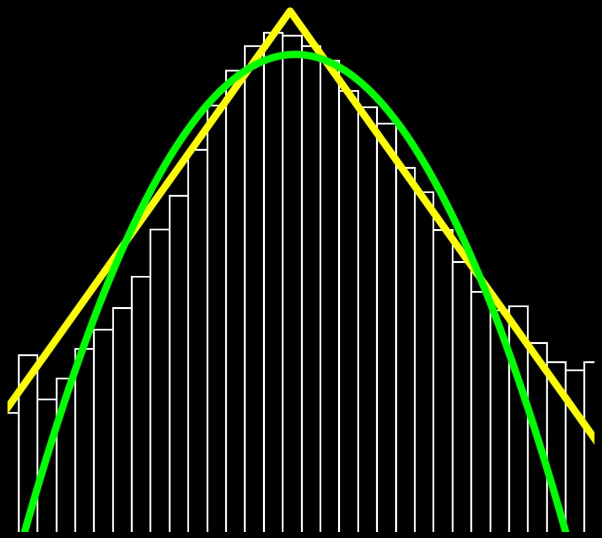
- Best to start difficult conversations early instead
- Acknowledge and embrace connections between information sources
- Develop modular terminology-based ontologies (AKA knowledge graph)
- Invest in metadata schema development. This is how to be strategic about how data is used.

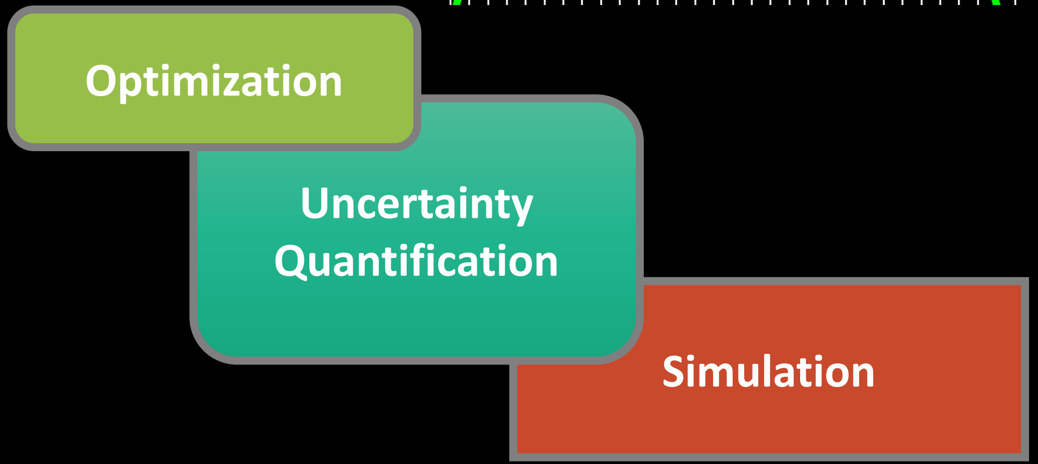


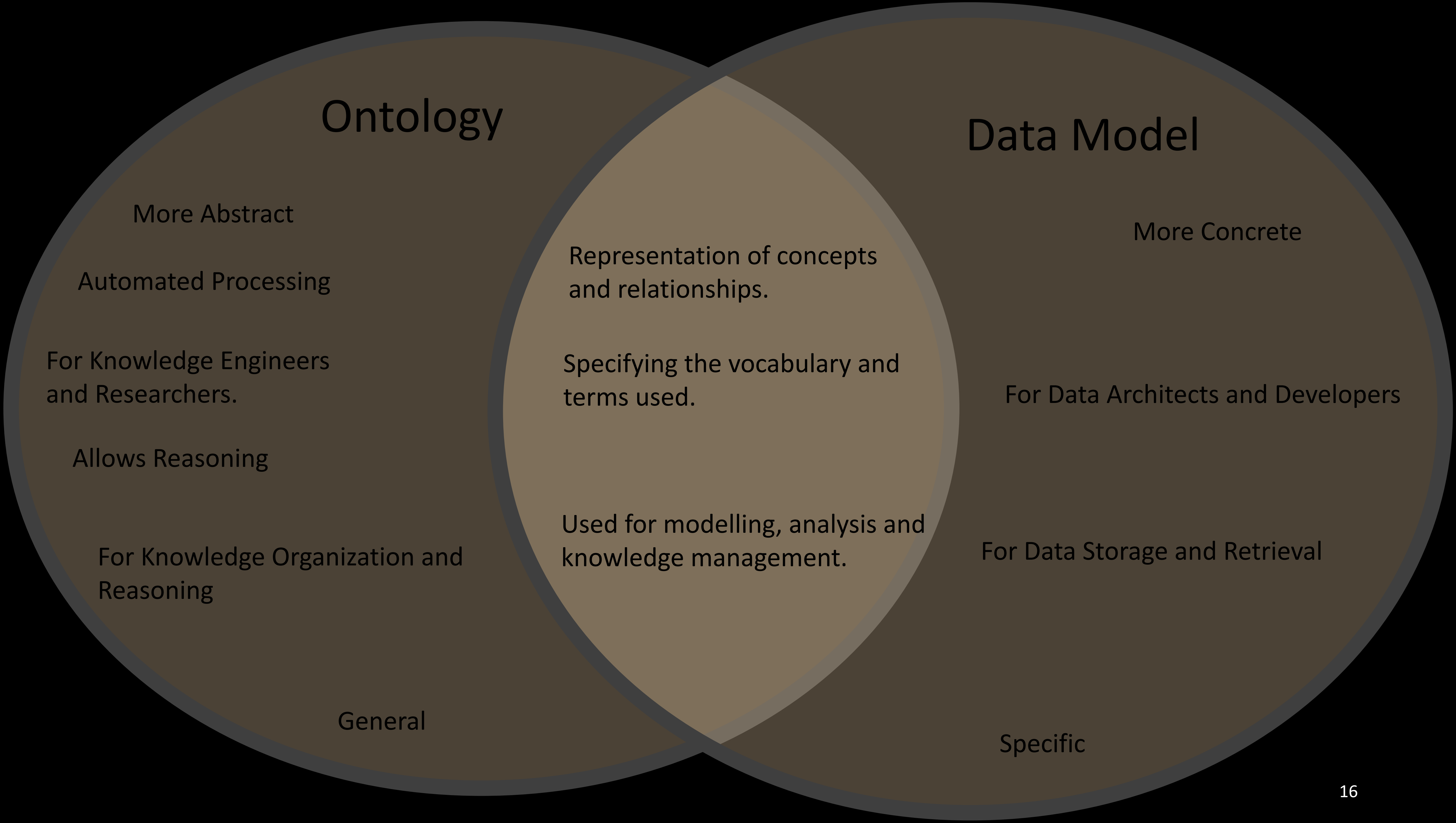
Conclusions



- Metadata schema allow strategic scoping of data campaigns
- There is a plethera of information that can be captured via uncertainty information
- Uncertainty metadata can enable a new generation of risk-informed designs via optimization under uncertainty
- Let’s continue the conversation! Email me at juqu@dtu.dk

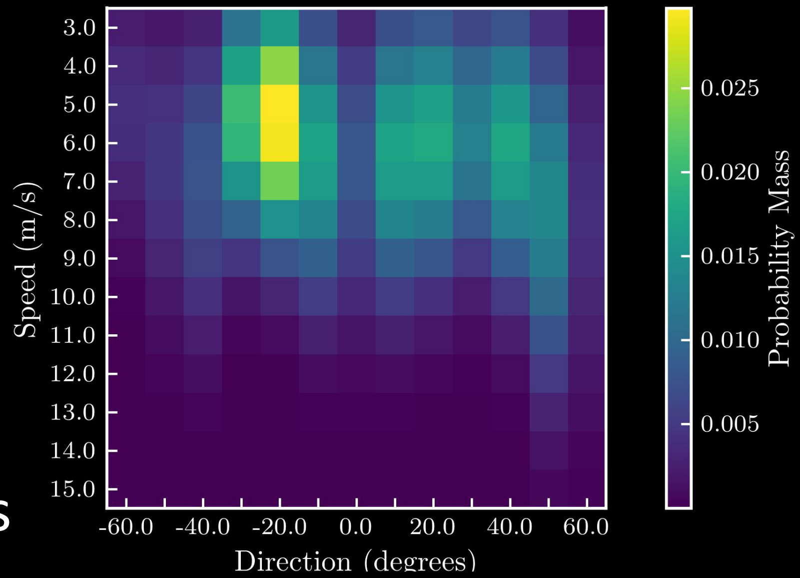


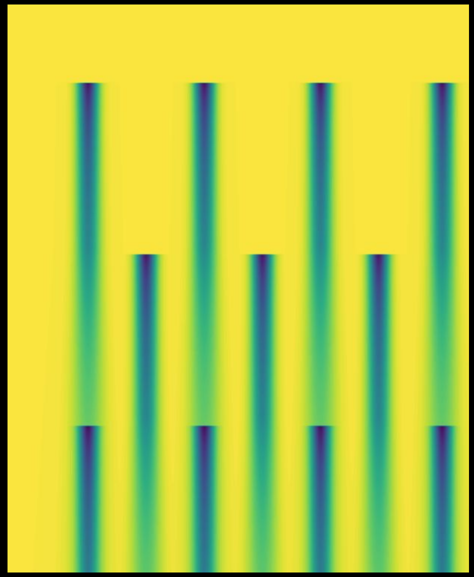


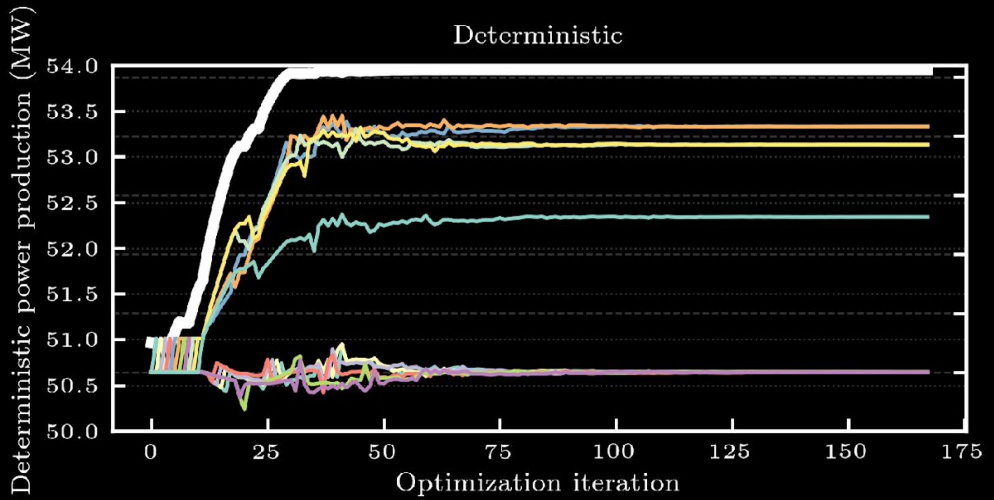

Ontology
Data Model
More Abstract
Automated Processing
For Knowledge Engineers and Researchers.
Allows Reasoning
For Knowledge Organization and Reasoning
General
Representation of concepts and relationships.
Specifying the vocabulary and terms used.
Used for modelling, analysis and knowledge management.
More Concrete
For Data Architects and Developers
For Data Storage and Retrieval
Specific

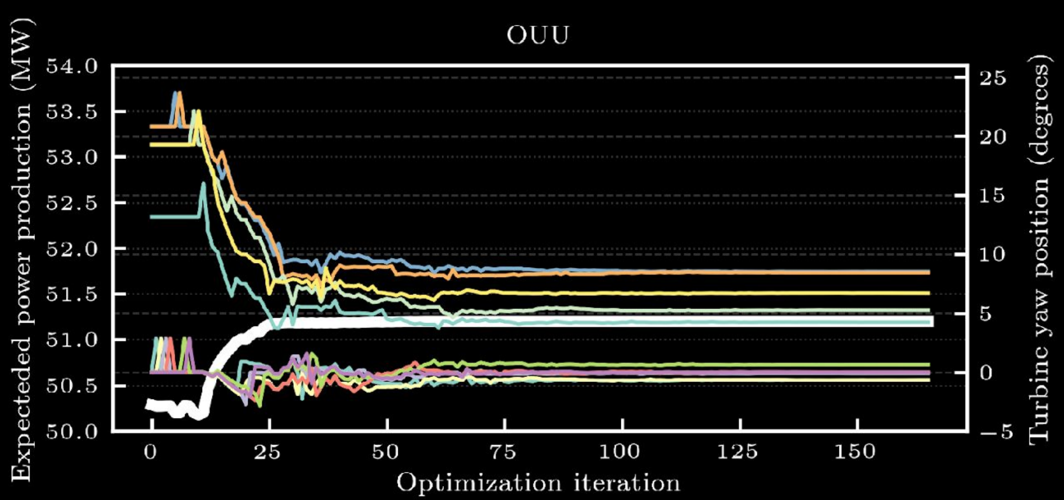
Wind Farm OUU

- Performed OUU for wind plant case considering uncertainty in speed and direction
- OUU generally favors lower yaw offsets









	Deterministic AEP (GWh)	Expected AEP (GWh)
OUU optimization	113.3	115.2
Deterministic optimization	114.0	114.7
Baseline strategy	111.1	114.6