Bond Liquidity with AI

MODELLING BID-ASK SPREADS USING DEEP LEARNING

Presentation at Budapest University of Technology and Economics

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What is Liquidity Research about?

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Agenda

1

Bond Markets and Bid-Ask Spreads

Why do we care about the bid-ask spread?

2

Data

What kind of data did we use and how did we pre-process it?

3

Models

What kind of models did we build and why?

4

Evaluation

How do you know which of two models is better?

5

Results

What can you expect from a deep learning model on a regression task?

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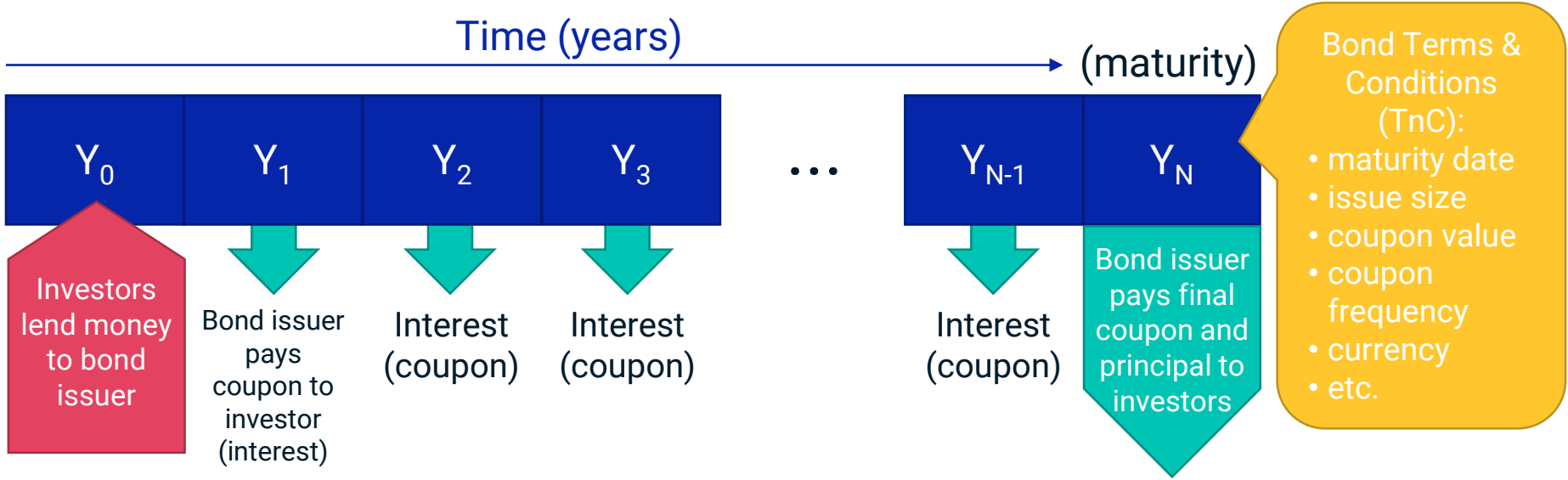
Bond Markets and Bid-Ask Spreads

WHY DO WE CARE ABOUT THE BID-ASK SPREAD?

What is a (corporate) bond?

- Debt: the corporation (bond issuer) borrows money from investors (bond holders) and pays it back with interest.

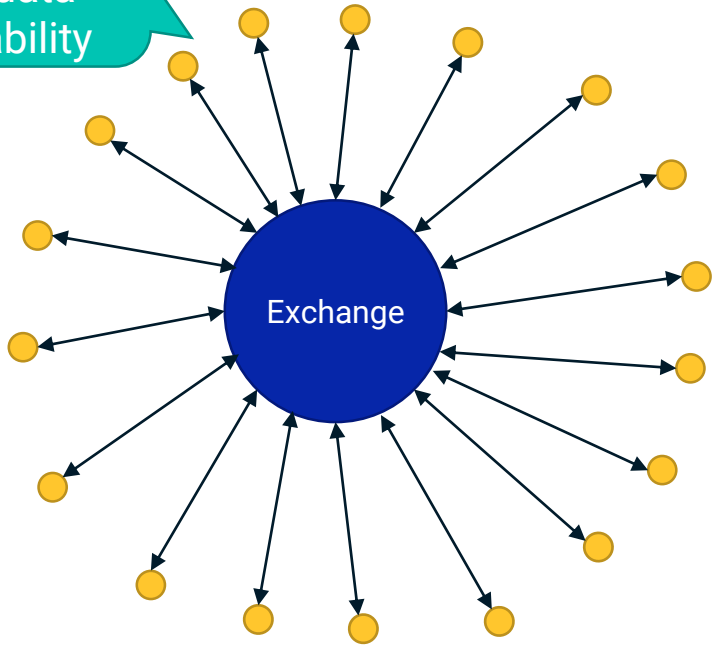


- **A bond can be sold during its term or held to maturity.**

Exchanges vs dealer markets

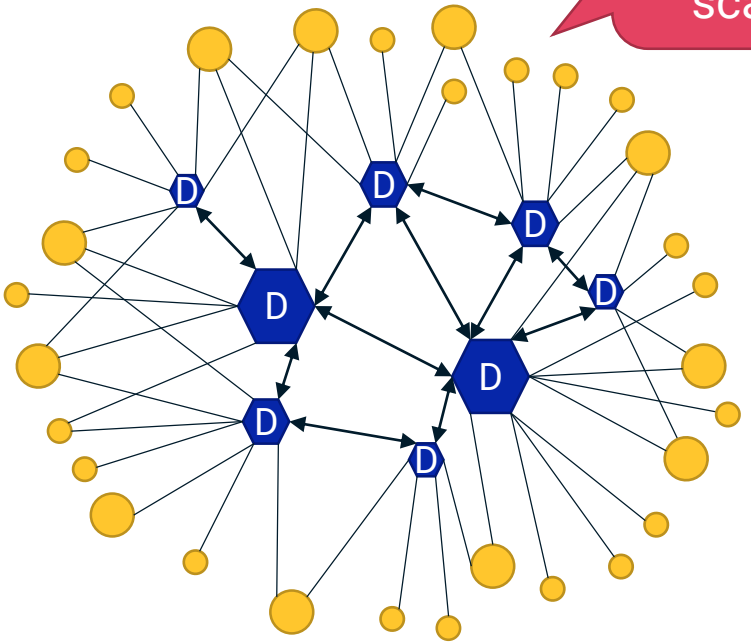
Higher transparency and data availability

Exchange markets



Dealer markets

Opaque and data is scarce!



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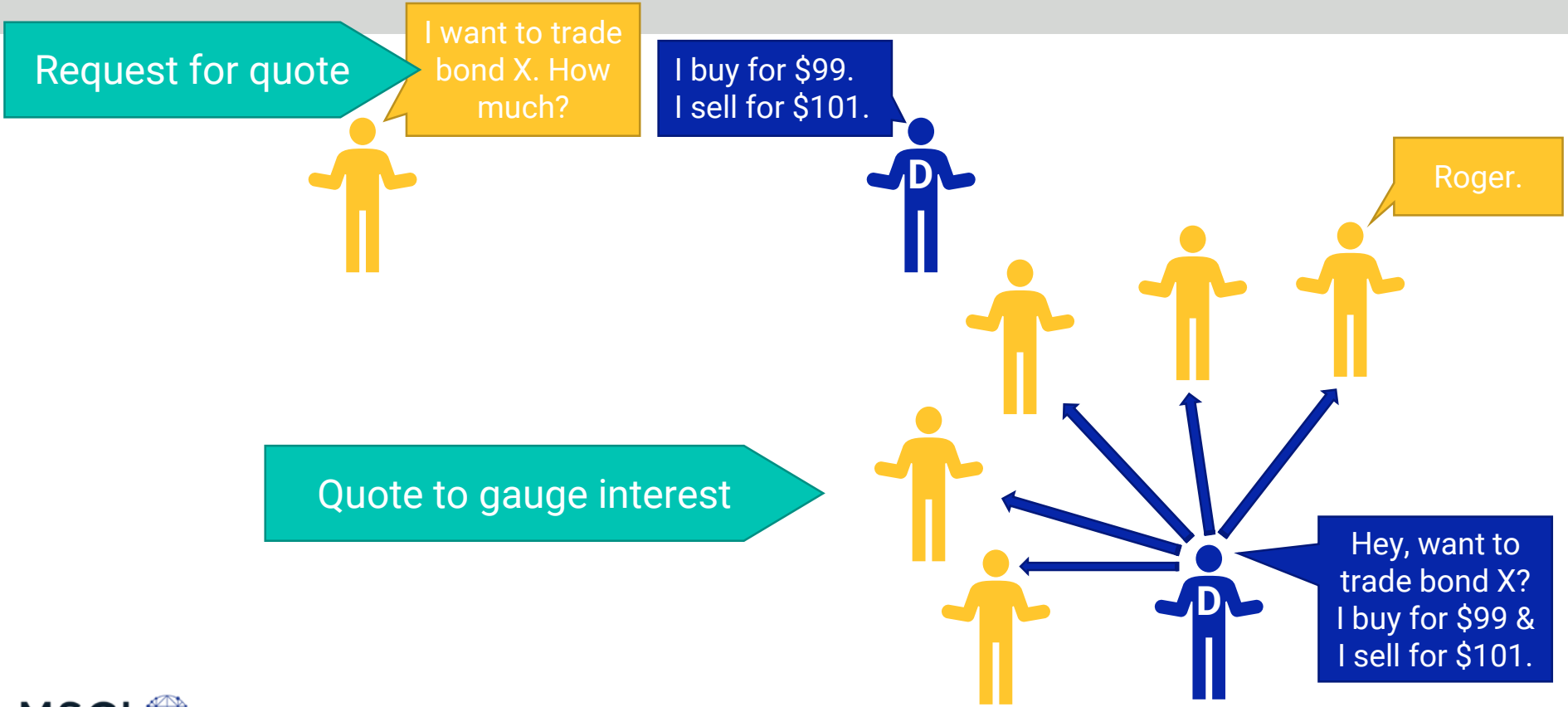
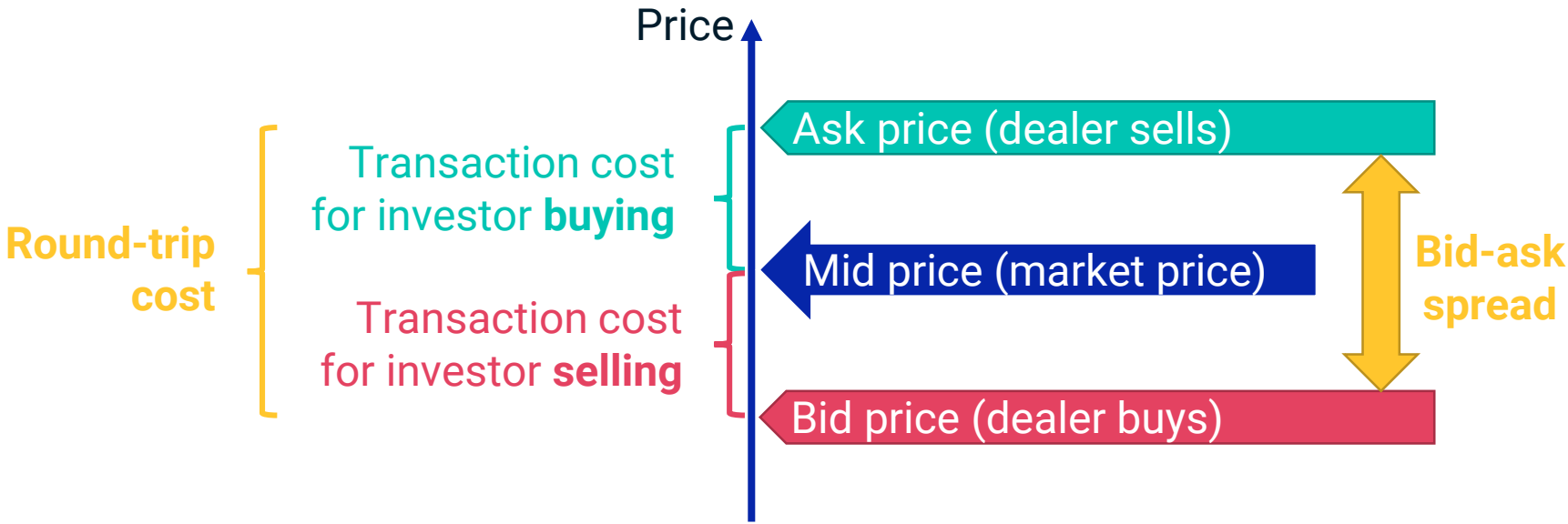
Trading in dealer markets – what are quotes?



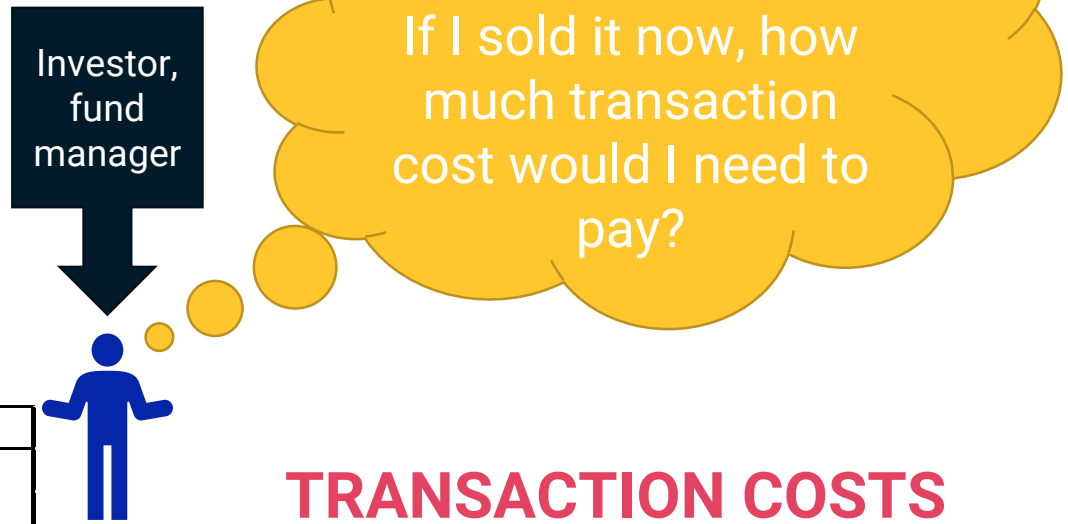
How dealers make money: the bid-ask spread



Why do investors care about bid-ask spreads?

- Investor buys bond with bid-ask spread of 1% (or 100bps) → 50 bps (0.5%) cost
- Price of the bond increases by 2% → Expect to sell at profit = 1%.
- But what if the bid-ask spread increases to 250 bps?
- Profit 0.2% instead of 1%.

	T0	T1 expected	T1 actual
Bid-ask spread	100 bps	100 bps	250 bps
Ask price	100.5	102.51	103.275
Mid price	100	102	102
Bid price	99.5	101.49	100.725
Profit		1.0%	0.2%



TRANSACTION COSTS EAT INTO PROFITS!

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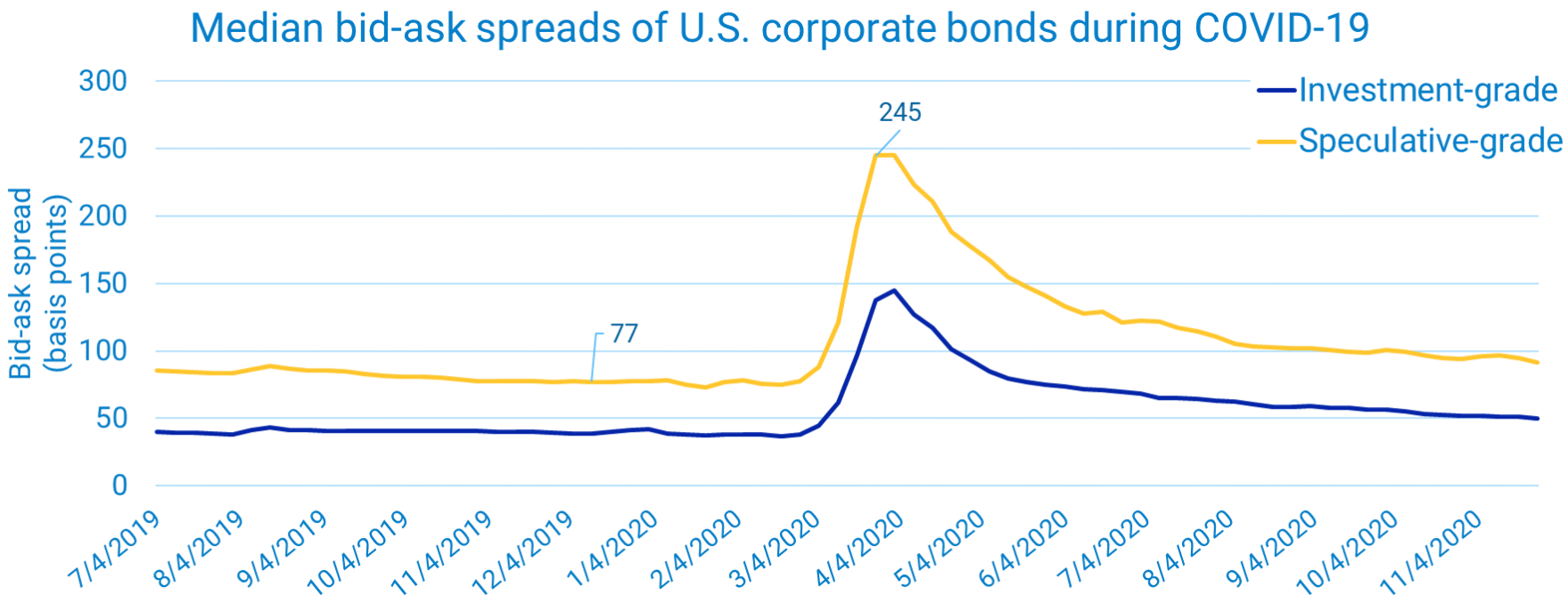
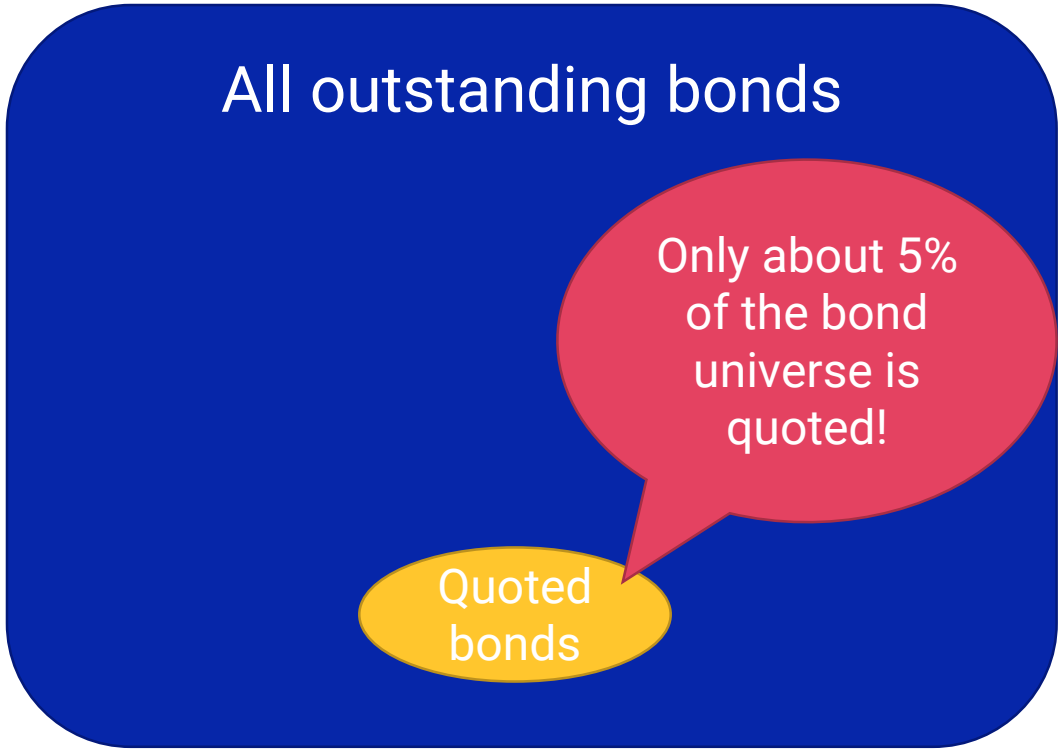
Liquidity during the COVID-19 crisis

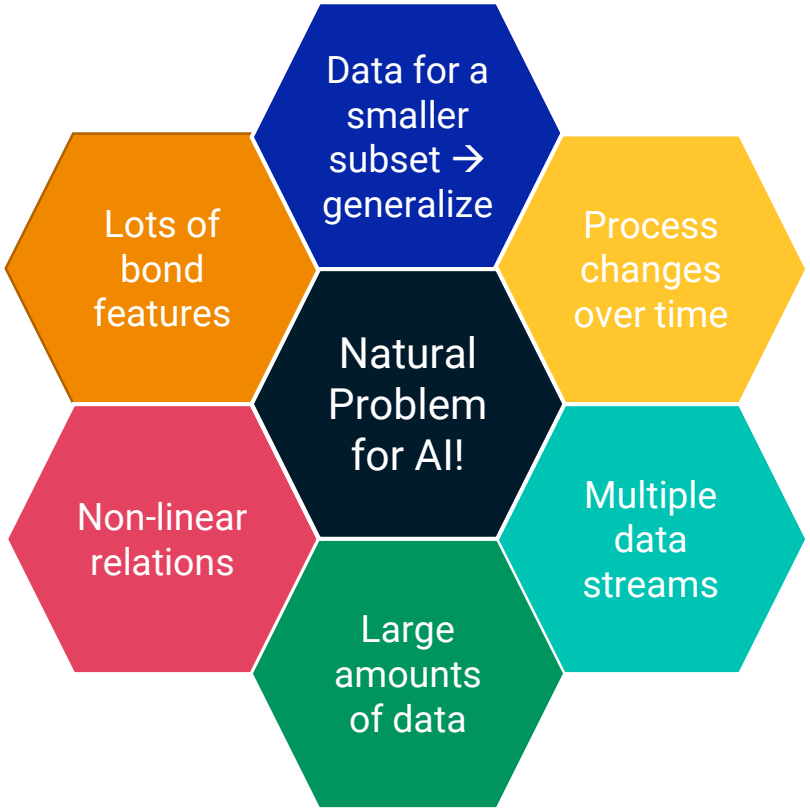


So how do we know the bid-ask spread?

- Trade reporting (delayed, difficult)
- Request quotes from dealers
- Dealers send out quotes to gauge interest → can be parsed
- Not all bonds are quoted/traded, only a fraction
- Many bonds are in buy-and-hold portfolios → held to maturity
- Similar bonds tend to have similar liquidity → we can use quoted bonds to predict bid-ask spreads of non-quoted bonds



A natural problem for AI!



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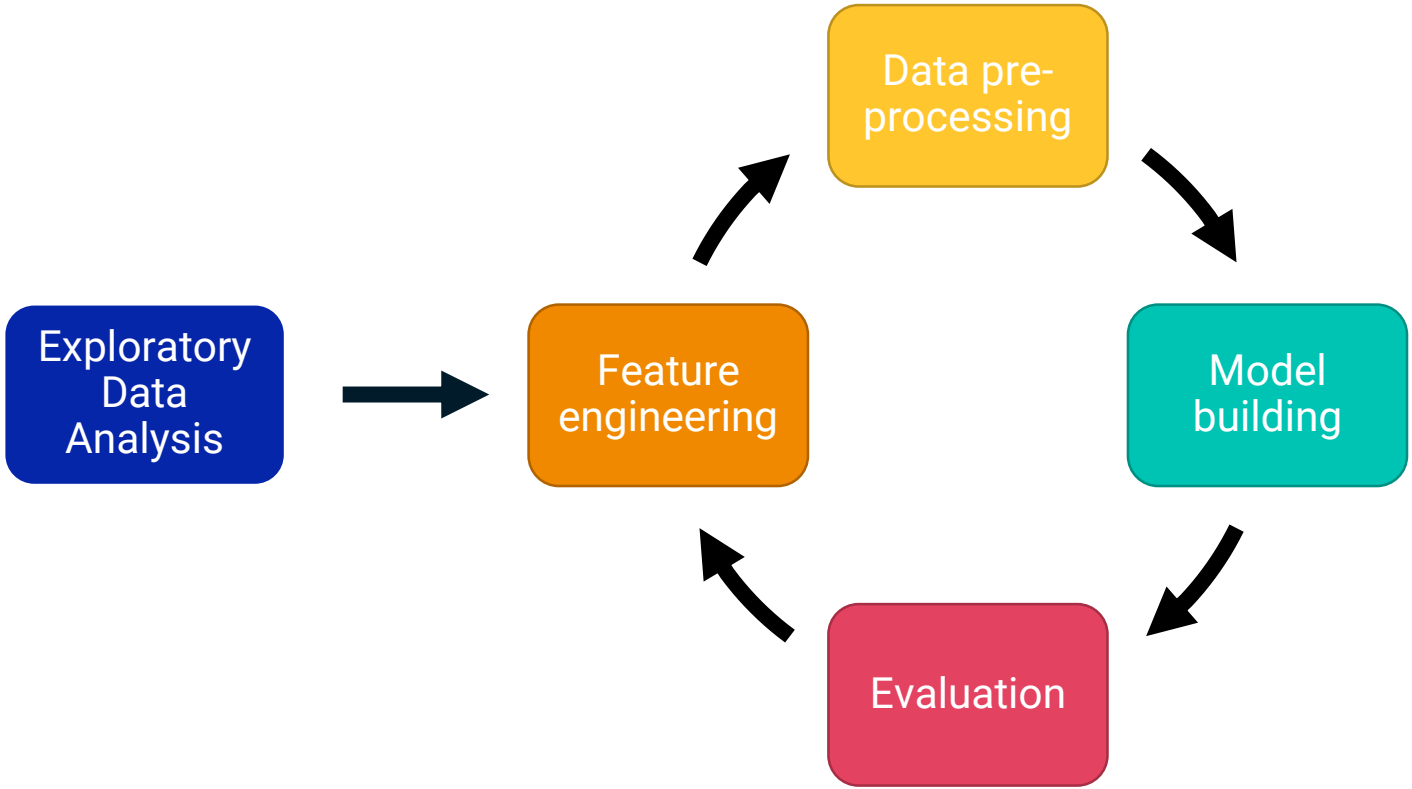
The modelling process



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Data

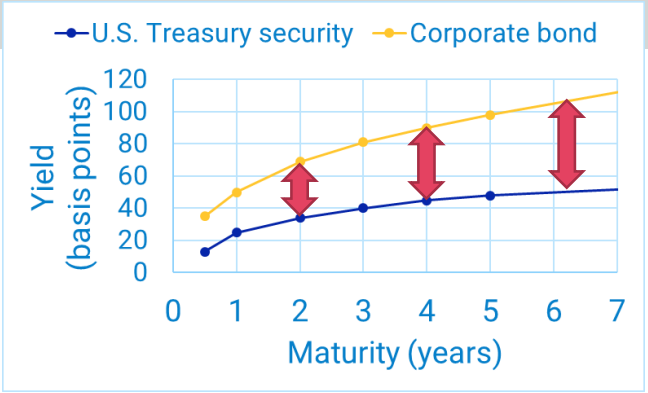
WHAT KIND OF DATA DID WE USE AND HOW DID WE PRE-PROCESS IT?

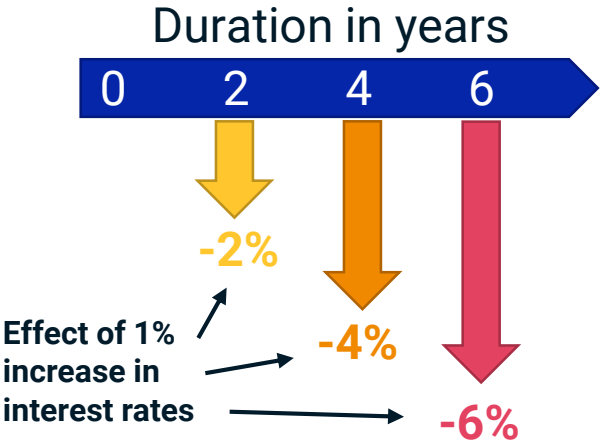
The “label”

- A single positive continuous number: a regression problem

The “features”

- Bond meta data **100+ features**
  - coupon and other interest terms, bond age, outstanding amount, region and country, sector and industry, bond rating, etc.
- Credit spread **single number + time history**
  - a measure of the credit quality of the company
  - ~ how much more interest (%) the corporate bond must pay than government bonds (calculated from market price)
  - depends on probability of default (failing to make payments)
  - depends on recovery (% of bond price investors will get if the company’s assets are liquidated due to default)
- Duration **single number + time history**
  - a measure of bond price sensitivity to interest rate changes
  - ~ % change in bond price due to an interest rate change of 1%
  - depends on time to maturity, interest terms, etc.





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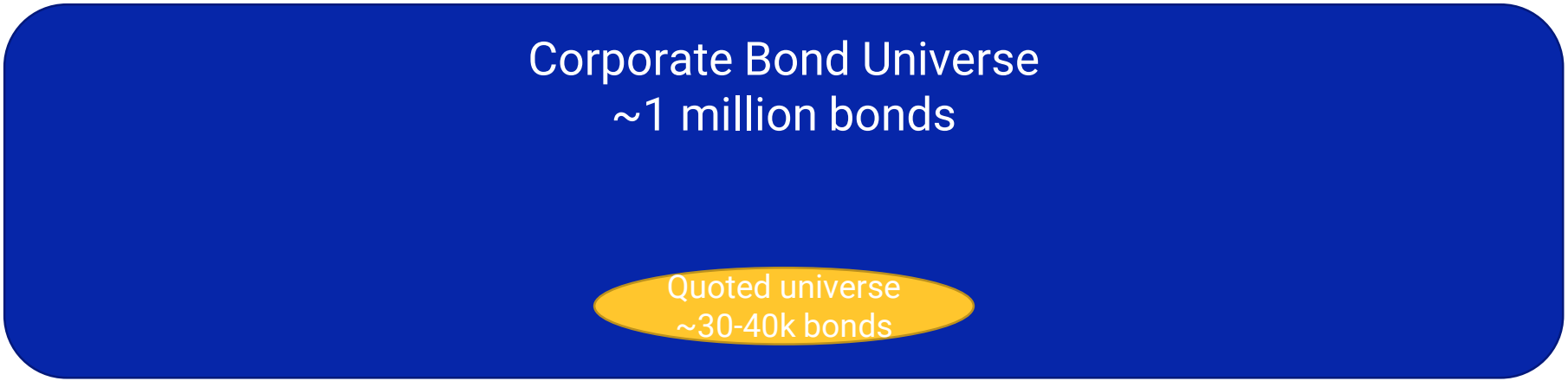
The amount of data

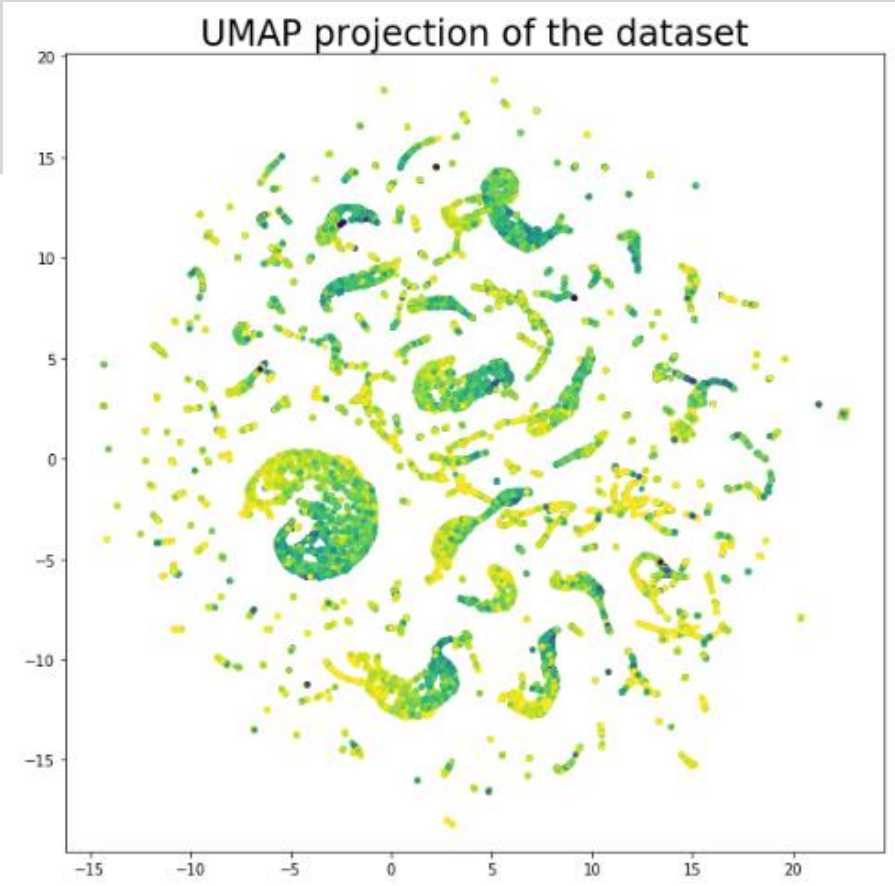
- ~30-40k quotes per day for corporate bonds – “labelled” data
- ~500k with all calculated features (credit spread, duration, etc) – “unlabelled” data
  - requires market price!
- ~100-150 columns (“features”)
- ~8-10 GB of data per year



Data pre-processing

- Add calculated features
- Add derivatives for time history features
- Outlier filtering
- Caps & floors (Winsorizing)
- Feature scaling
  - Standardising, min-max scaling, etc
- Handling missing values
- Train-valid-test split (60/20/20)

- Exploratory Data Analysis (EDA) and data cleaning / pre-processing is about **70%** of a machine learning project!



Uniform Manifold Approximation and Projection for Dimension Reduction

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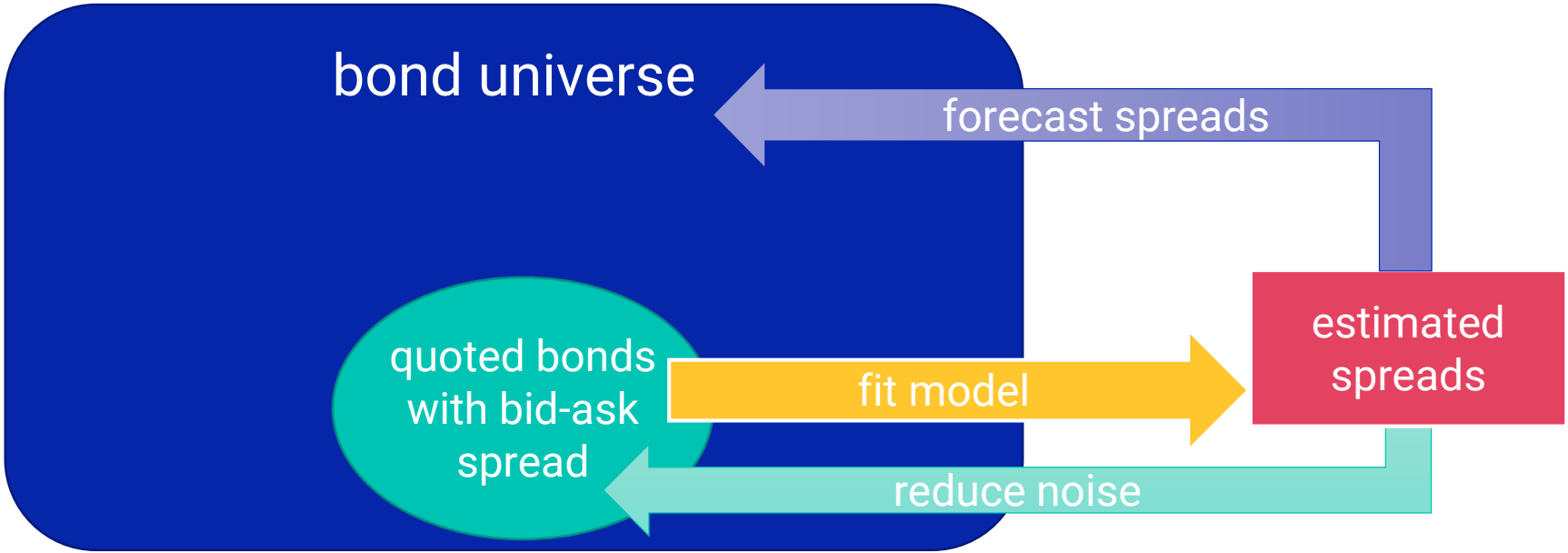
Models

WHAT KIND OF MODELS DID WE BUILD AND WHY?

What is the modelling task?



Baseline models

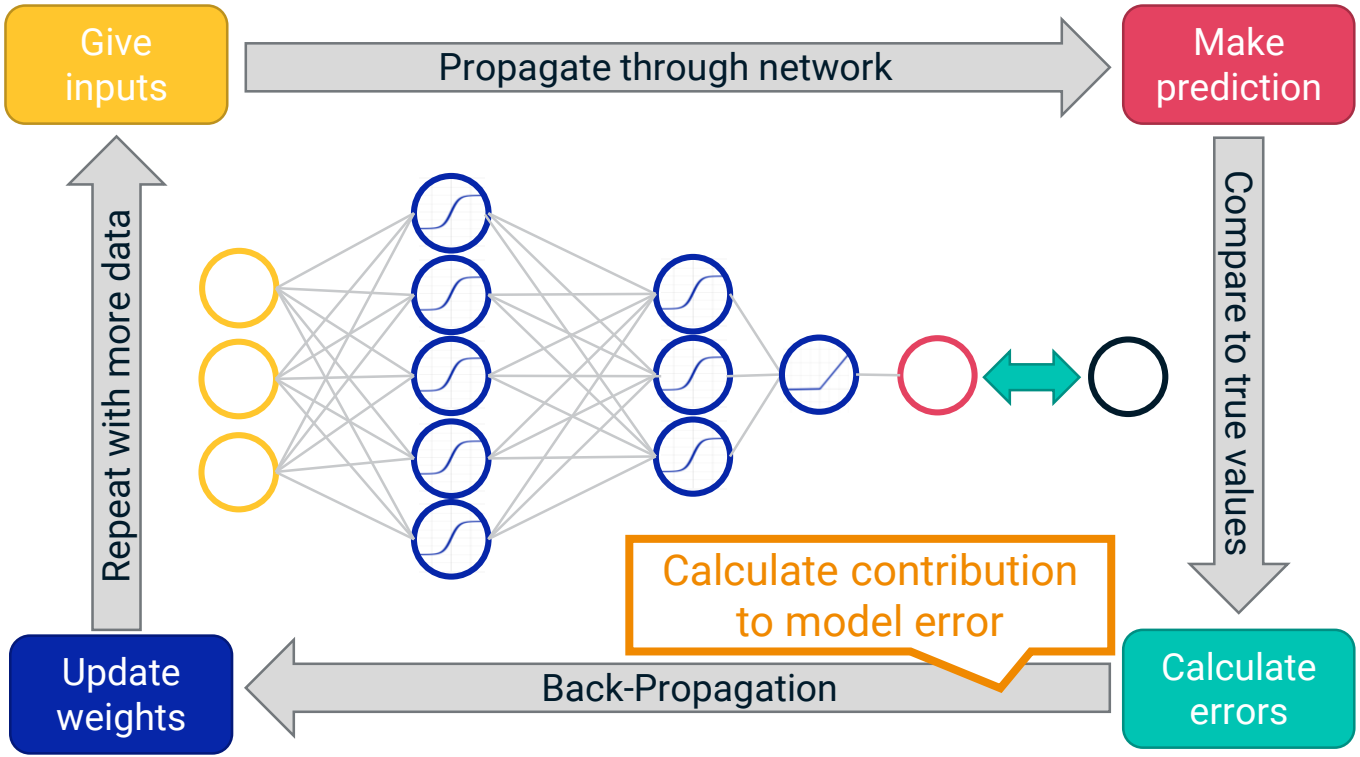
- Naïve estimator: the bid-ask spread tomorrow will be the same as today
- Mean prediction: the bid-ask spread of each bond will be predicted as the mean of the quoted universe
- Linear regression: simple linear regressions using subsets of variables
- Current MSCI model:
  - **Cross-sectional** model – based on data from a single day
  - **Two-stage regression** model

$$BAS = (\beta_1 \cdot C + \beta_2 \cdot D) \cdot e^{\gamma_0 + \gamma_1 \cdot O + \gamma_2 \cdot A + \gamma_3 \cdot B + \gamma_4 \cdot S}$$

  - First stage: linear regression
  - Second stage: regression on the first stage's residuals
  - Second stage regressors are multipliers

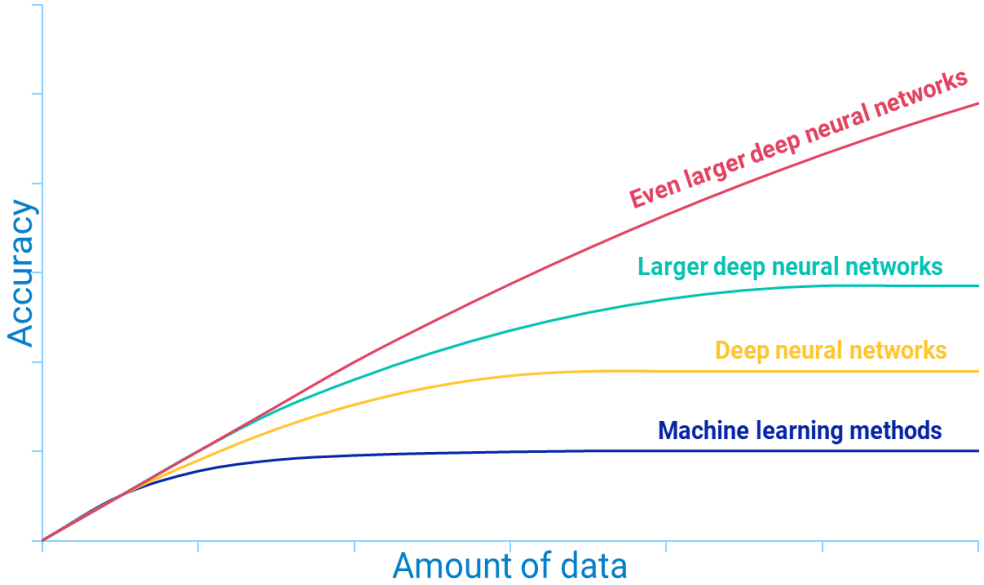
- First stage
  - C – credit spread
  - D – duration
- Second stage
  - O – outstanding amount (issue size)
  - A – relative age of the bond (proportion)
  - B – dummy variable IsBank (whether the issuer is a bank)
  - S – dummy variable – IsSubordinated? (whether it is a subordinated issue)

What is a Deep Neural Network and how does it work?



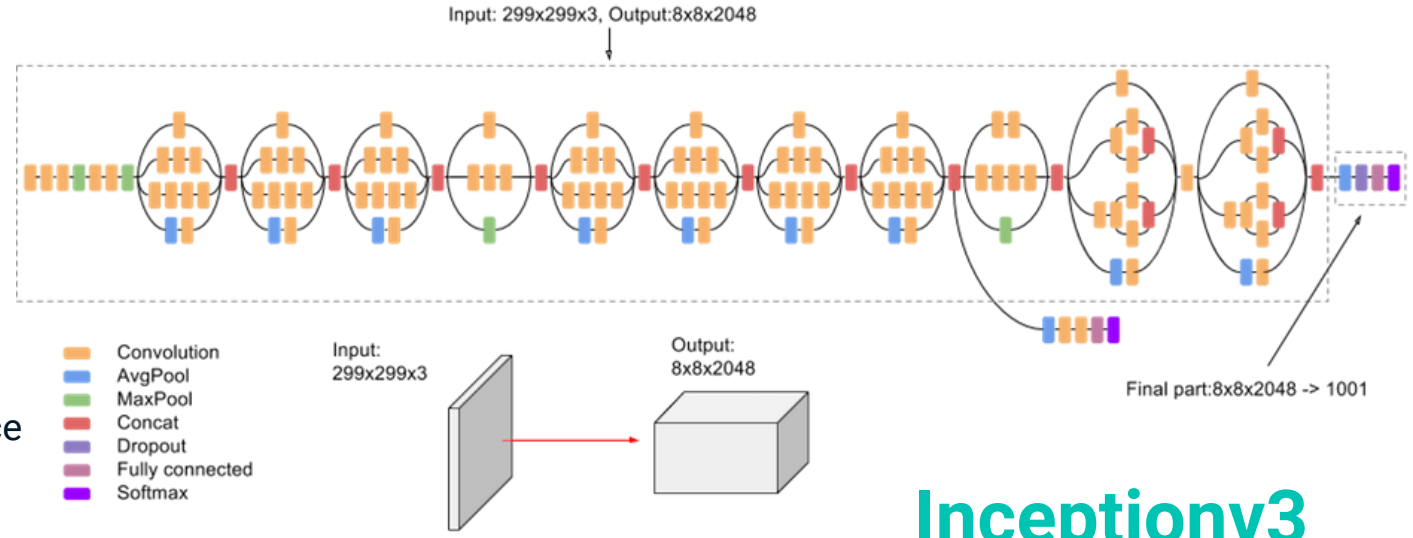
Why is deep learning powerful?

- Knowledge-based methods:
  - Rule-based, parametric
- Data-driven methods:
  - Machine learning (linear regression, SVM, k-means, random forest, etc):
    - More dependence on the preparation of data
  - Deep learning:
    - Representation learning instead of feature engineering – works together with modelling
- Hybrid models:
  - Used for most machine learning and deep learning applications
  - E.g. knowledge-based caps and floors on outputs, filters on inputs



This is a novel problem!

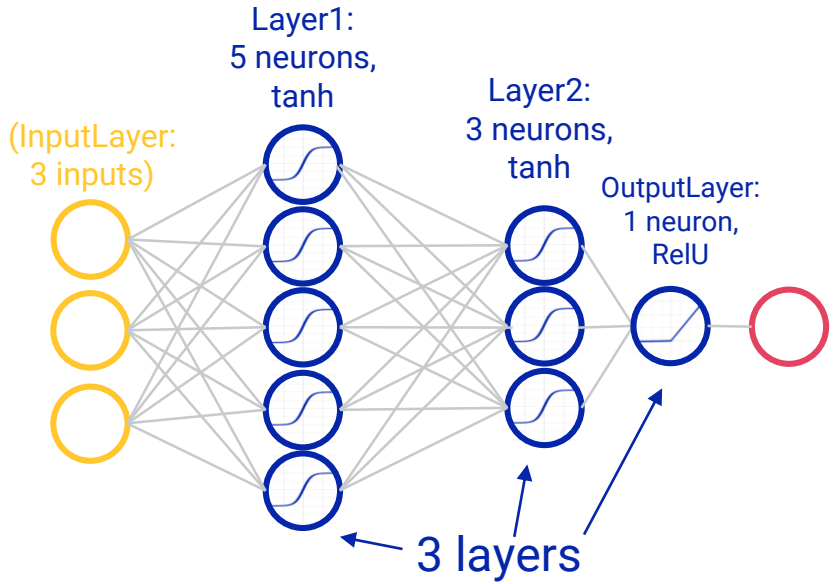
- Standard machine learning projects:
  - lots of people,
  - lots of data,
  - giant networks,
  - lots of hyperparameter optimization
  - on high-performance machines
- A novel problem:
  - there are no published network designs!
  - find architecture that works



Inceptionv3

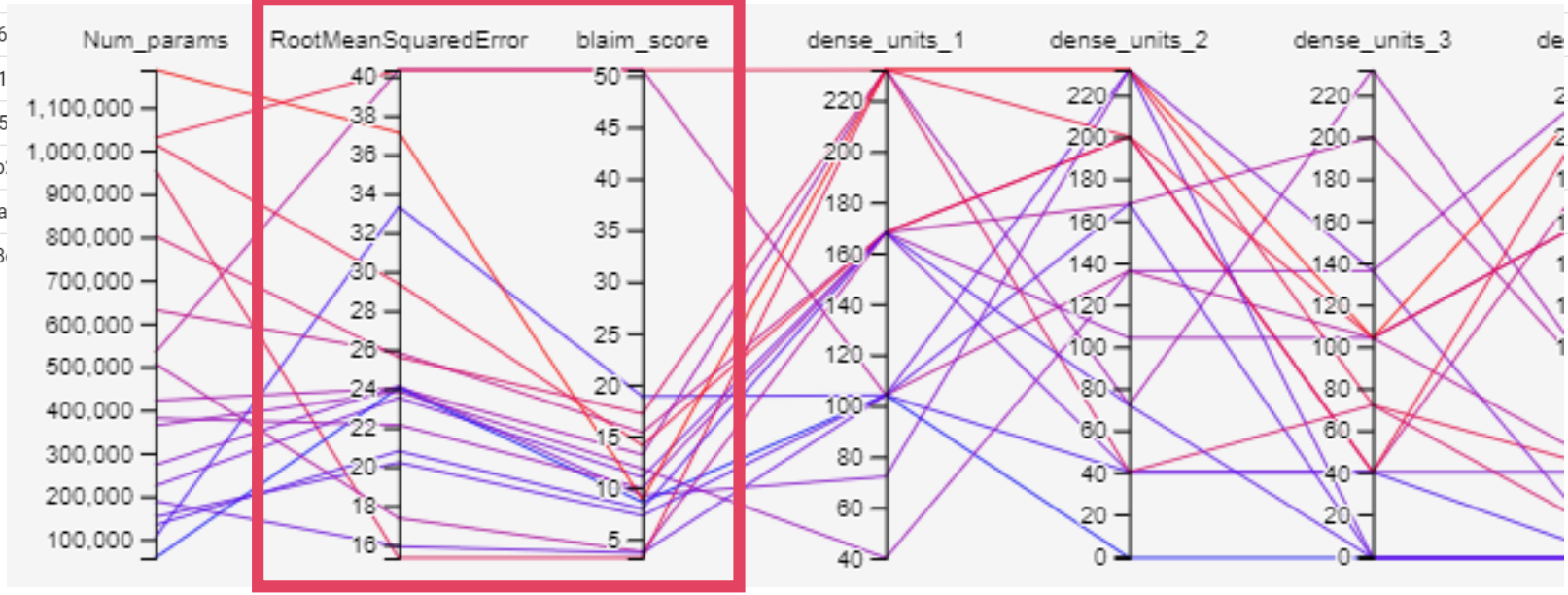
Dense networks of increasing complexity

- 2-layer basic network
- 5-layer manual “logical” network
  - dropout
  - ResNets (skip connections)
- Hyperparameter optimization
  - Choosing the parameters of the network itself
  - number of layers
  - number of neurons in each layer
  - activation function
  - learning rate
  - etc.
- Hyperopt results:
  - 4-6 dense layers
  - large dropout rates (50-75%), i.e. only a small subset of features are actually used
  - larger first layer (128/256), then small layers afterwards (64/32)



Hyperparameter optimization

Show Metrics	Trial ID	RootMeanSquaredError	blaim_score	Num_params	lr	num_layers	dense_units_1	dense_units_2	dense_units_3	dense_units_4	dense_units_5	dense_units_6
☐	070139d1558ea3...	33.308	18.838	1.0439e+5	0.010000	3.0000	104.00	40.000	40.000	-1.0000	-1.0000	-1.0000
☐	22fec23ebb41d42...	40.335	50.554	5.3229e+5	0.010000	7.0000	104.00	136.00	104.00	40.000	136.00	168.00
☐	24dfe8d382ec343...	25.819	15.339	6.3091e+5	0.00010000	7.0000	168.00	200.00	40.000	200.00	72.000	72.000
☐	2c92cebd382b6											
☐	3b93ae656c741											
☐	3ba3e9b0b5d35											
☐	4bf31e773b61b											
☐	799ae1c10a2da											
☐	7e95f3d4694d8											



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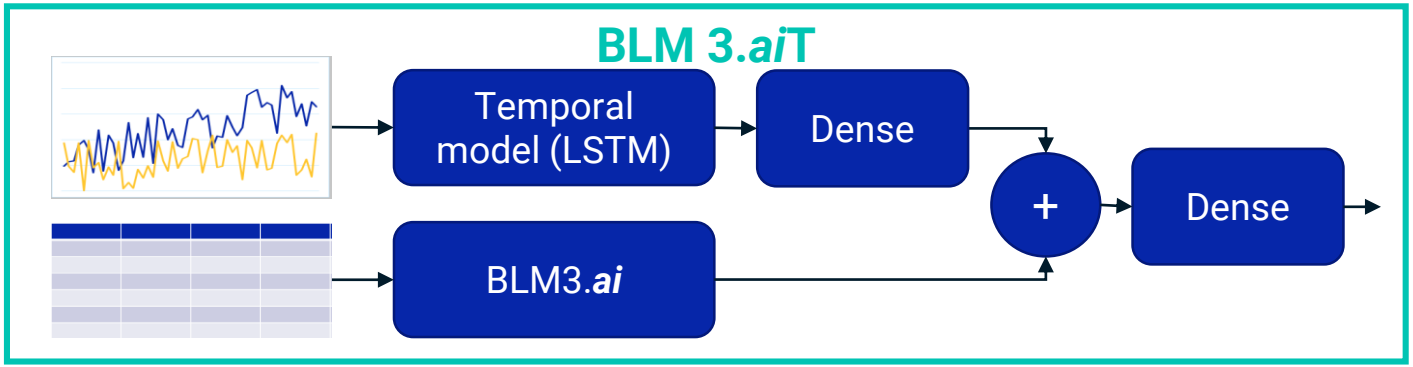
Temporal models

- Using Long Short-Term Memory (LSTM) cells
- Allows for connecting time history variables
  - includes time evolution, looks back several days rather than just cross-sectional modelling
  - can capture dynamics / derivatives
- Simple version: concatenate LSTM and dense network outputs at the end



- (Advanced version: use hyperopted network output as initial states of LSTM)

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Evaluation

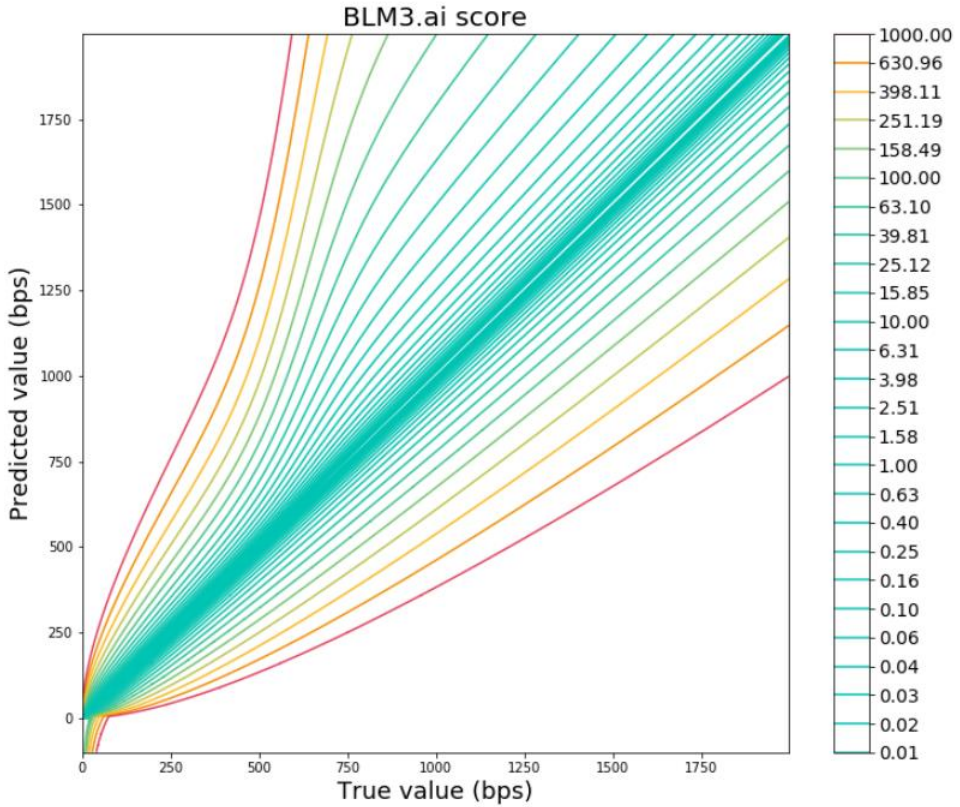
HOW DO YOU KNOW WHICH OF TWO MODELS IS BETTER?

Getting closer to the real world

1. Evaluation metric bias:
   - should be based on client preference rather than a mathematical formula
2. Cross sectional models vs future prediction
   - single day vs predicting for the days ahead
3. In-sample leakage
   - is our test set really independent?
4. Statistical evaluation
   - factor in randomness

Evaluation metrics bias

- How to evaluate models?
- RMSE? R^2? Average absolute error? Median abs. error? Percentiles?
- Custom metric based on client need (i.e. expected usage), not just a mathematical expression!



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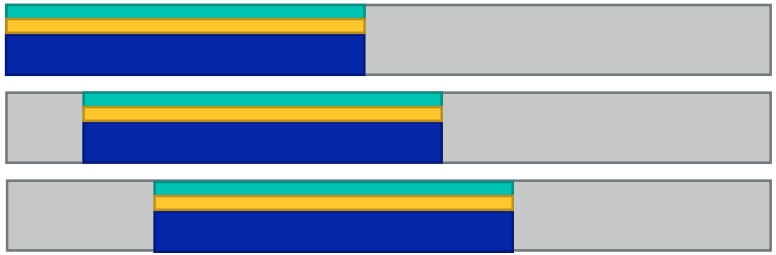
Cross-sectional vs future prediction scenarios

- Train – validation – test set split

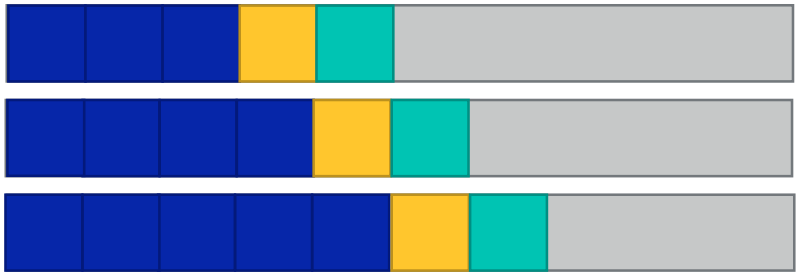
1. Cross section every day

2. Larger cross sectional model (e.g. 5 days)



3. Constant-size moving window

4. Increasing training set moving window



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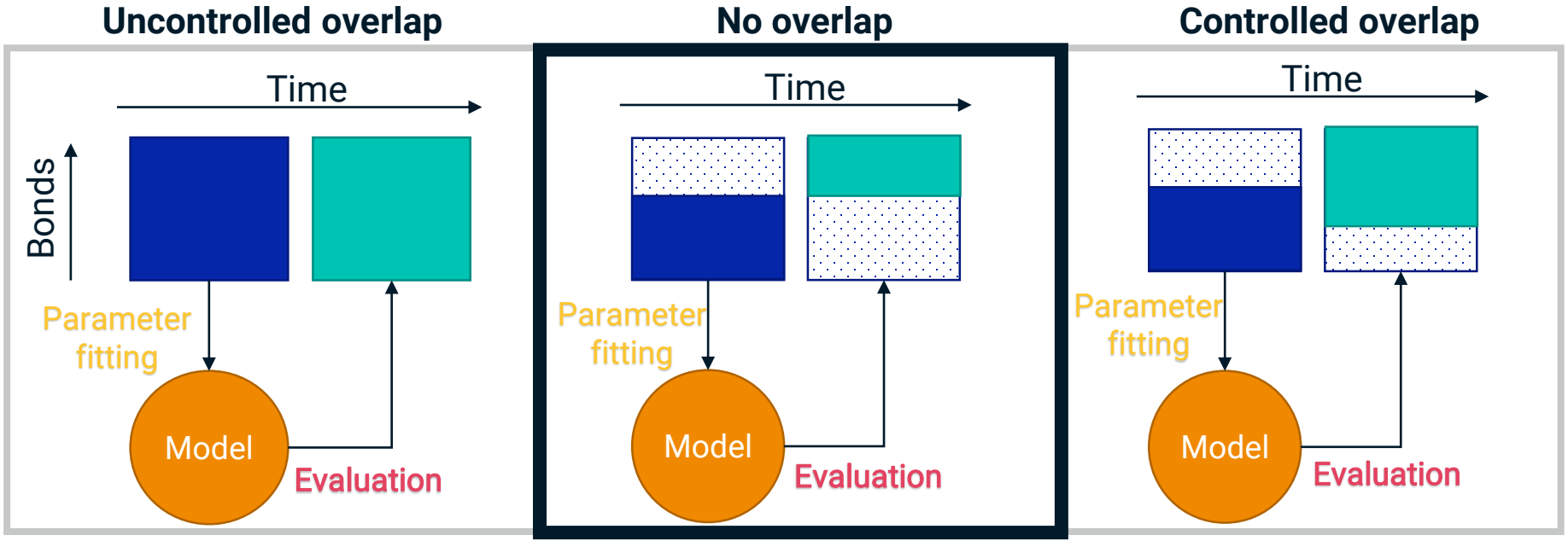
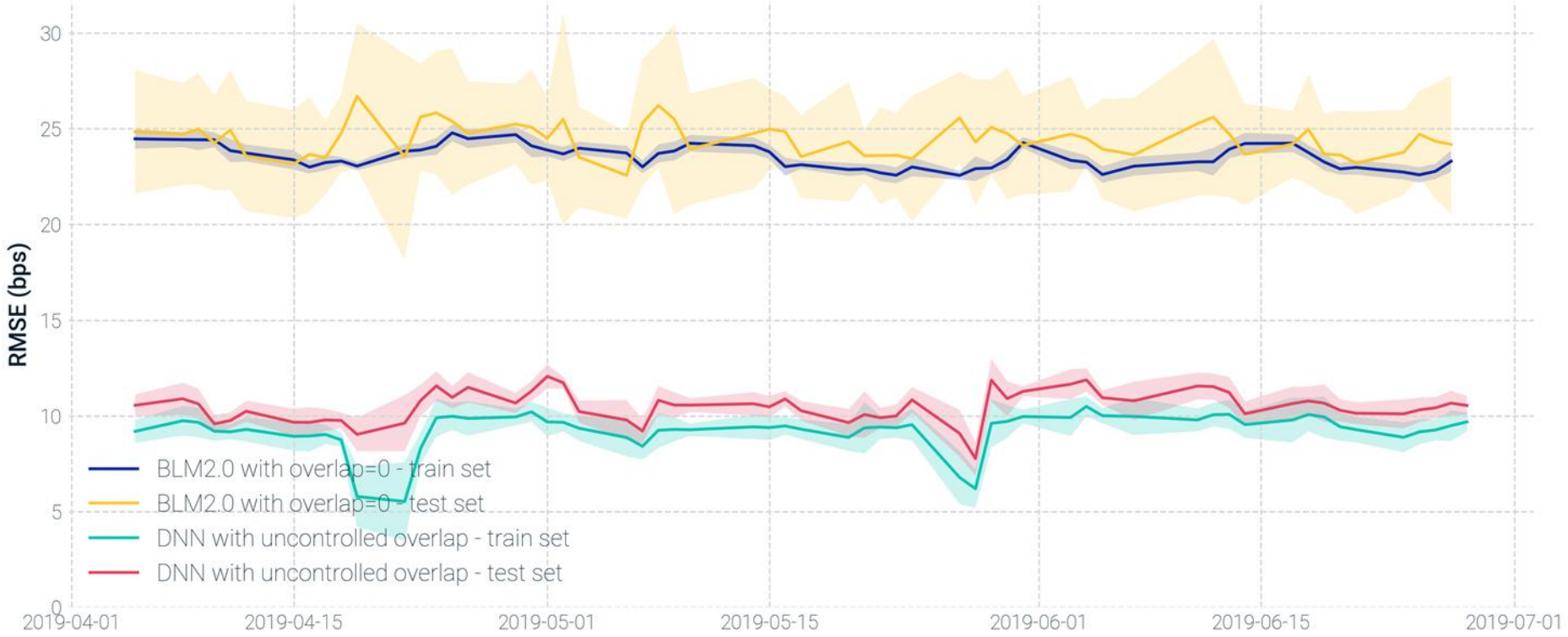
In-sample leakage

- Issue: evaluation using quotes for the same bonds that were used for training



In-sample leakage and overfitting - 1



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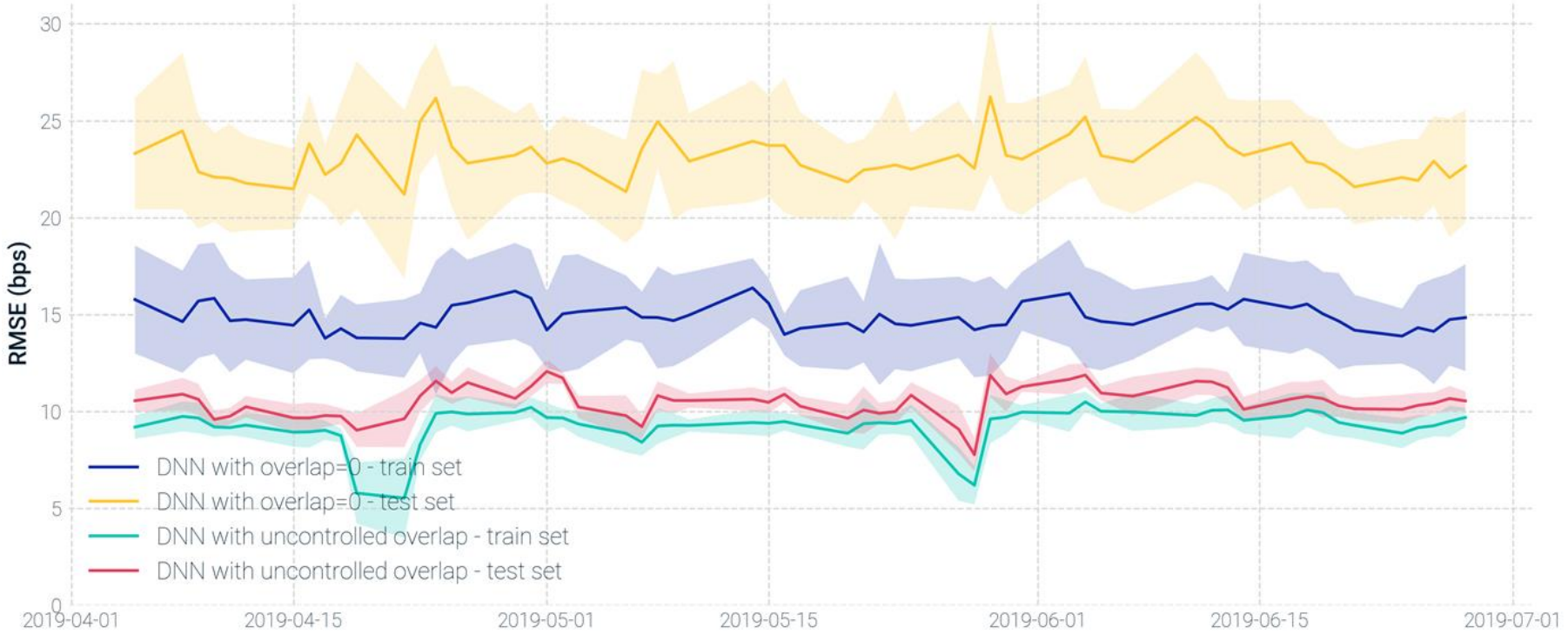
In-sample leakage and overfitting - 2



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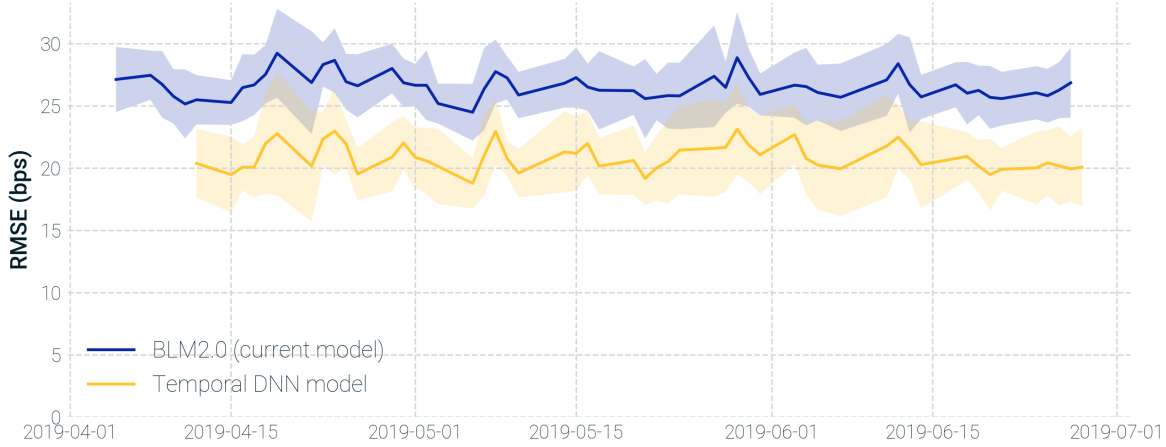
Statistical evaluation of test set results

- Multiple factors cause uncertainty / randomness:
  - Biased train – validation – test set selection
  - Initial weights of the network (less important)
  - Hyperopt process
- Evaluation should be statistical
  - 10-20-50 runs each day
- Backtesting: improvements that are stable over time increase confidence (even if bands overlap)



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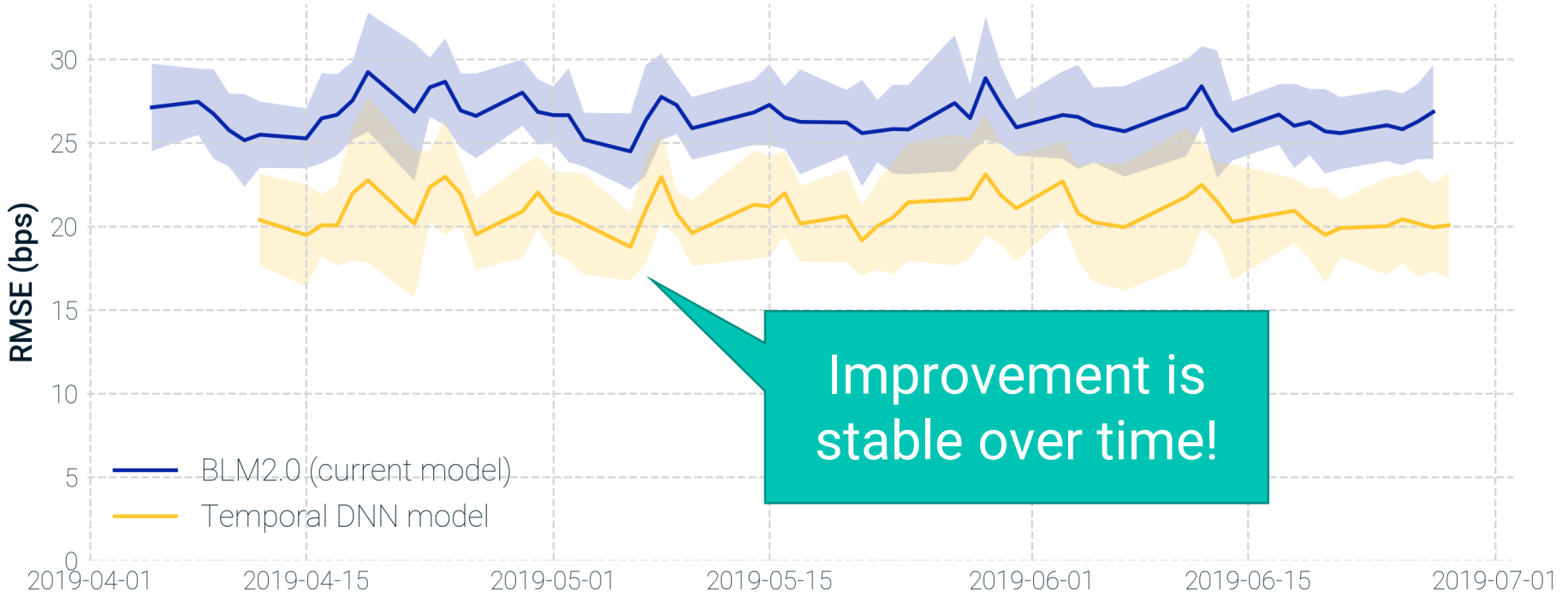
Results

WHAT CAN YOU EXPECT FROM A DEEP LEARNING MODEL ON A REGRESSION TASK?

What did we expect to achieve?

1. Linear regression tends to be OK for regression tasks
2. Our existing model is more sophisticated than linear regression:
   - two-stage regression
   - can model non-linear relationships
3. It was not clear in advance that any improvement can be achieved
4. At the outset:
   - 10% improvement → successful project
   - 15% improvement → quite good results
   - 20% improvement → expected best-case scenario when backtesting over the long term

Stable and significant improvement in calm periods



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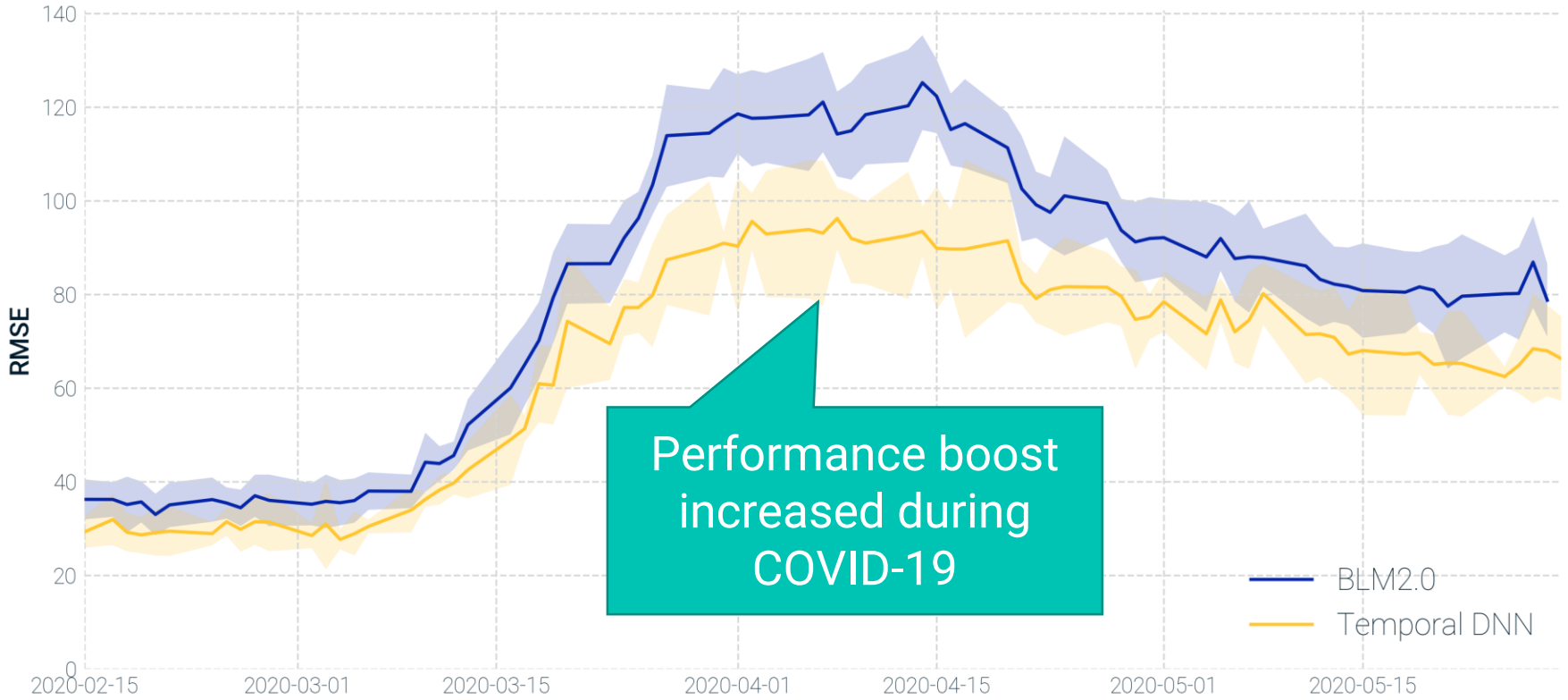
Improvement more significant during a crisis period



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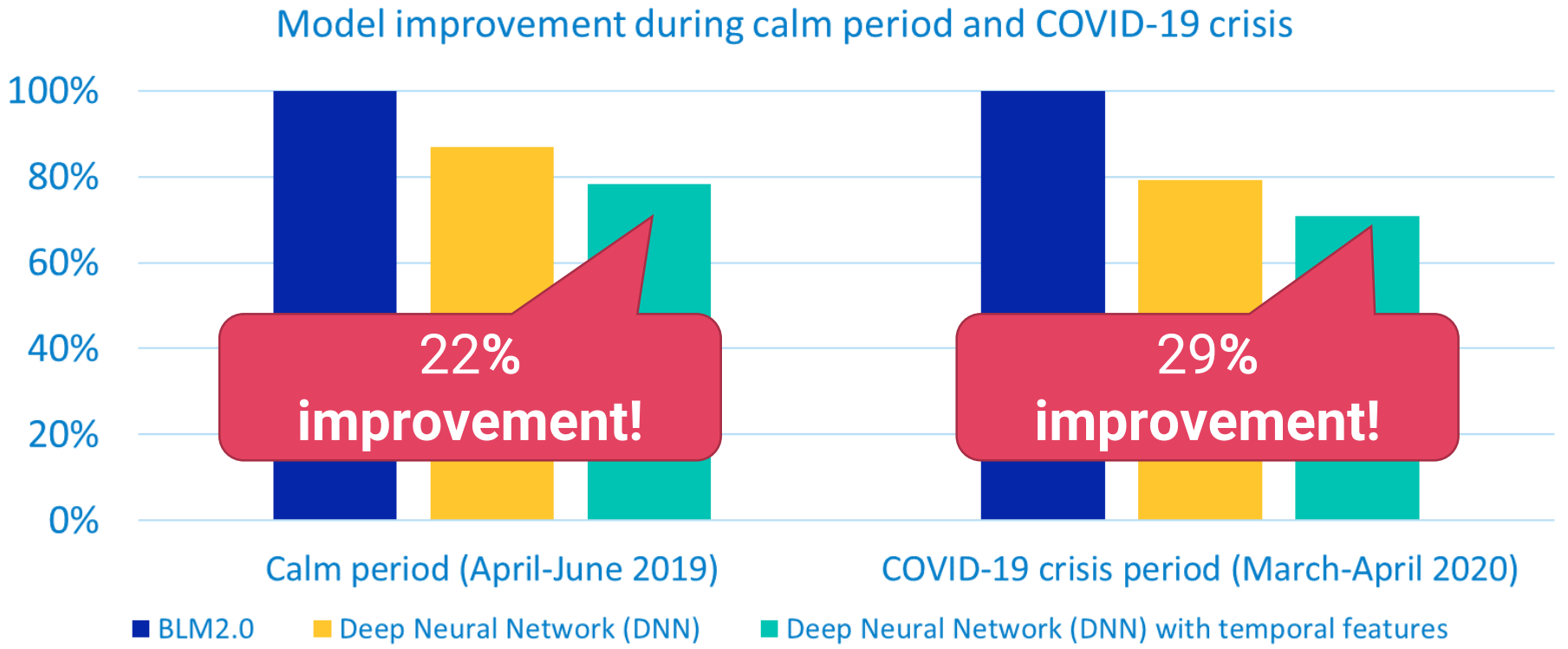
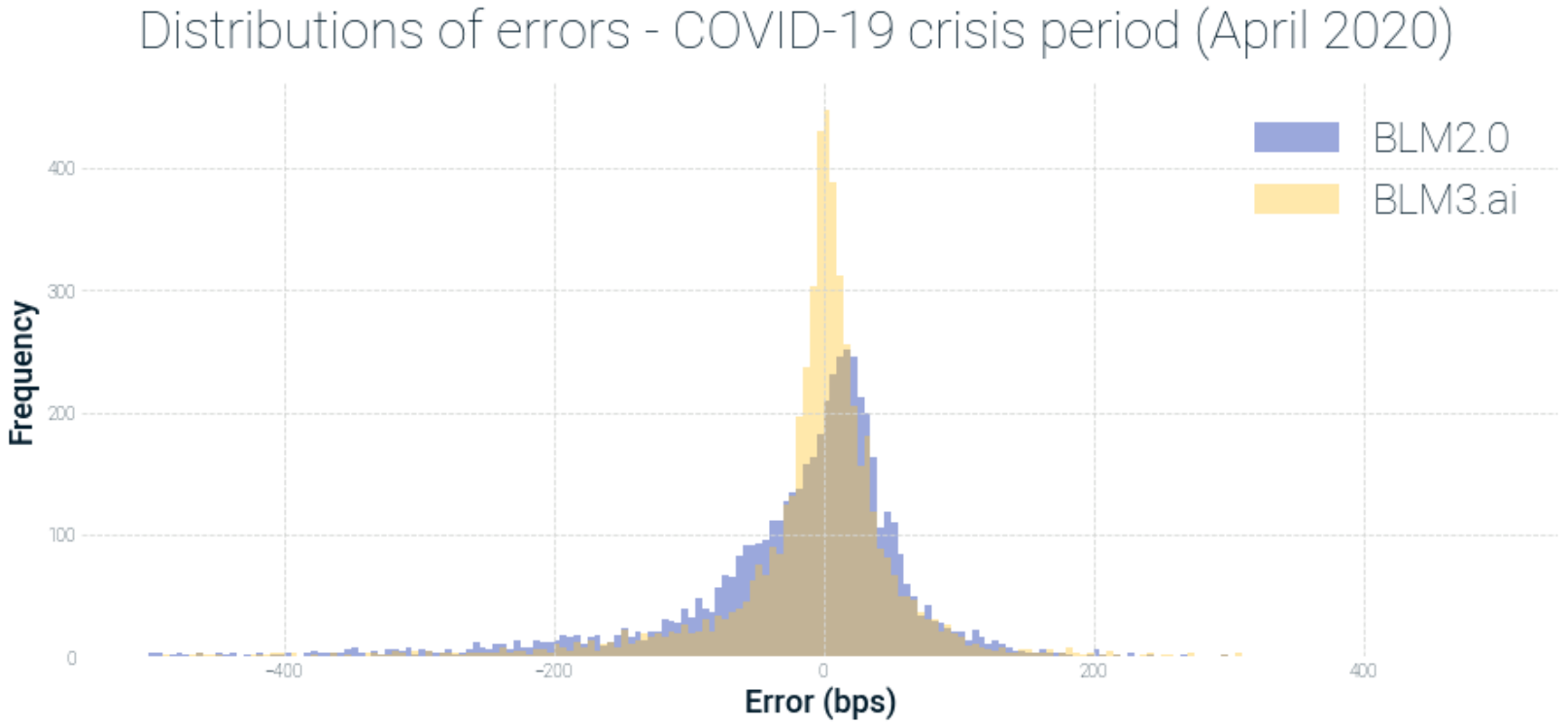
Overall performance



RMSE is not the full picture...



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