DEEL
DEpendable & Explainable Learning

OBJECT DETECTION WITH PROBABILISTIC GUARANTEES: A CONFORMAL PREDICTION APPROACH

Florence de GRANCEY, Jean-Luc ADAM, Lucian ALECU,
Sébastien GERCHINOVITZ, Franck MAMALET, David VIGOUROUX

OBJECT LOCALIZATION

DEEL
DEpendable & Explainable Learning

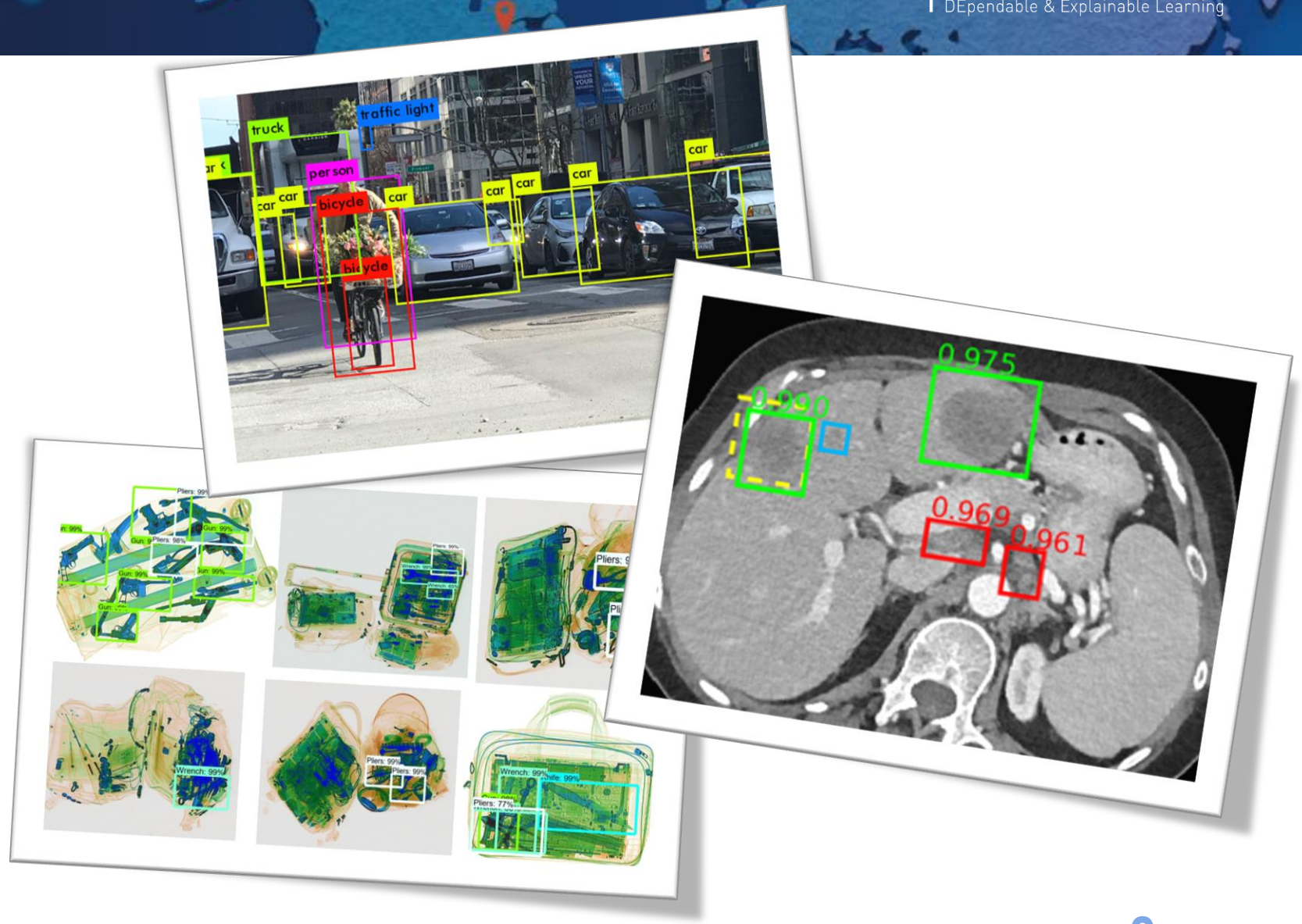
Object detection

- Classification
- **Localization**

(focus of this paper)

Applications

- Autonomous driving
- Medical diagnosis
- Anomaly detection
- etc.



RELIABLE UNCERTAINTY QUANTIFICATION

DEEL
DEpendable & Explainable Learning

- Uncertainty quantification for object detection
  - Deep Ensembles [1]
  - Monte-Carlo [2]
  - Direct modeling [3]
  - Bayesian networks [4]
  - Uncertainty Wrapper [5]
  - ….

Lack of formal guarantees

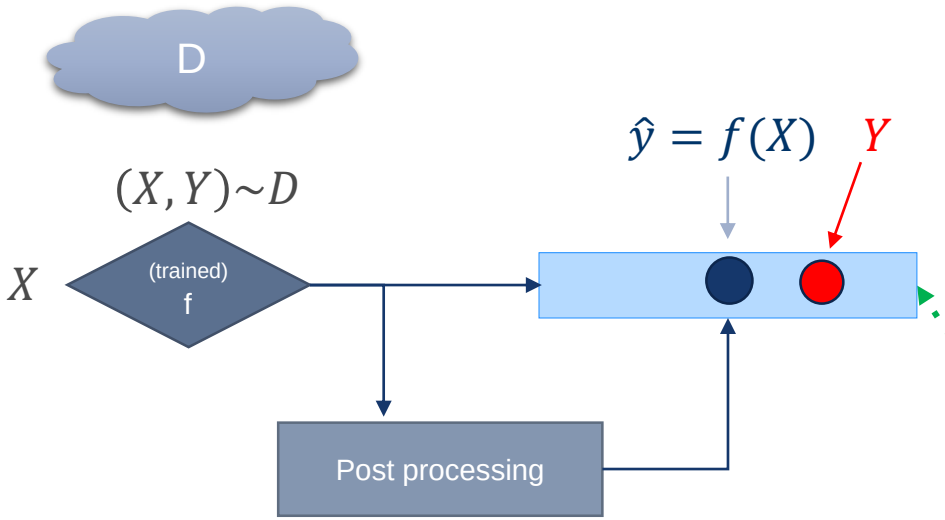
- In order to use ML predictions in ***safety-critical applications*** we need ***reliable uncertainty quantification***
  - **Conformal prediction**
  - Formal methods
  - PAC-Bayes learning
  - etc.

Theoretical guarantees

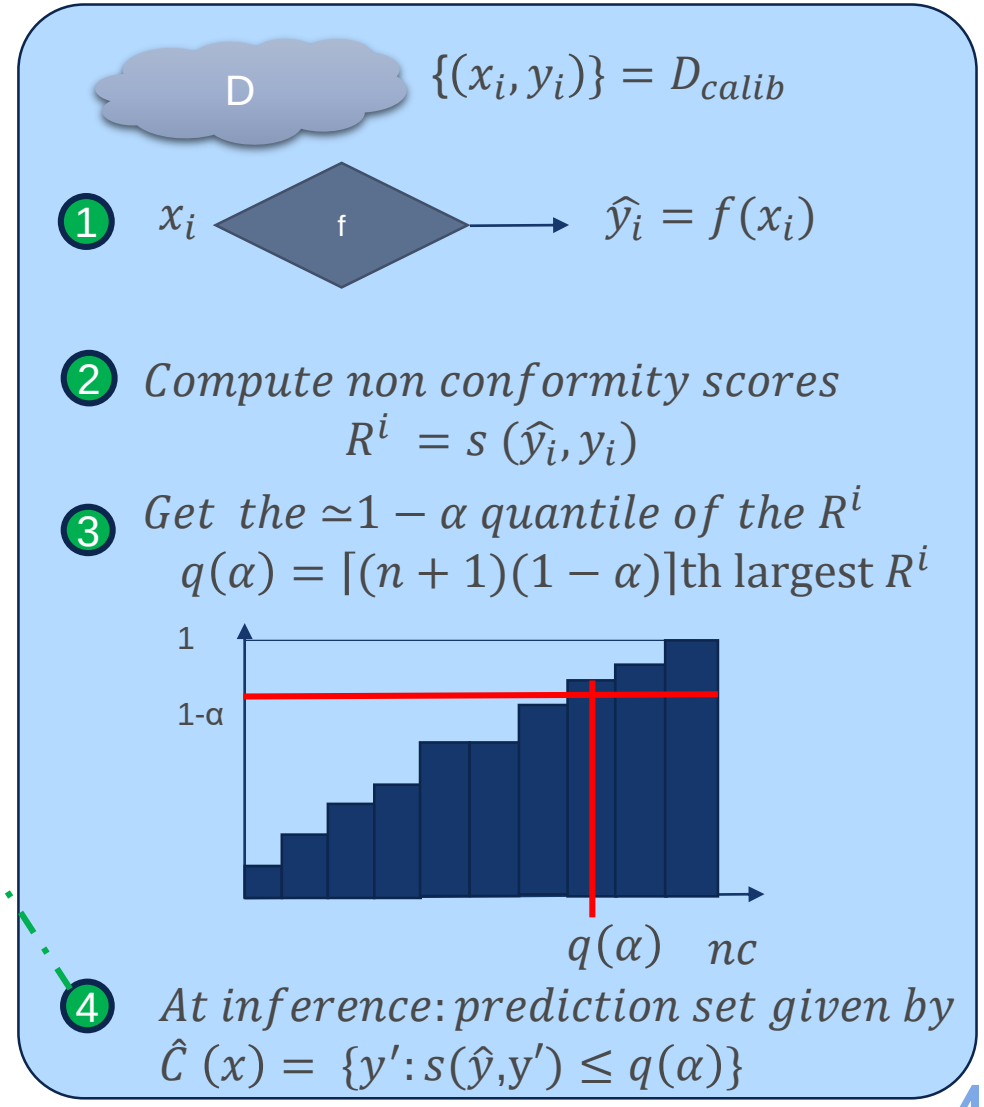
[1] Lyu, Z & al.: Probabilistic object detection via deep ensembles. In: ECCV'20
[2] Deepshikha, K. &al: Monte carlo dropblock for modelling uncertainty in object detection (2021), arXiv:2108.03614
[3] Le, M.T & al :Uncertainty estimation for deep neural object detectors in safety-critical applications. In: ITSC'18
[4] A. Harakeh & al : Estimating and Evaluating Regression Predictive Uncertainty in Deep Object Detectors
[5] Kläs, M., Sembach, L.: Uncertainty wrappers for data-driven models: Increasethe transparency of AI/ML-based models through enrichment with dependable situation-aware uncertainty estimates. In: WAISE'19 (2019)

CONFORMAL PREDICTION

GENERAL FRAMEWORK



Conformal prediction [1,2] = statistical framework that provides a *prediction interval or set* which, at a *desired risk level α,* contains the true value Y.



Split Conformal Prediction

[1] Vovk, V., Gammerman, A., and Shafer, G. (2005). *Algorithmic Learning in a Random World.* Springer.
[2] Angelopoulos, A.N., Bates, S. (2021). *A gentle introduction to conformal prediction and distribution-free uncertainty quantification.* arXiv:2107.07511

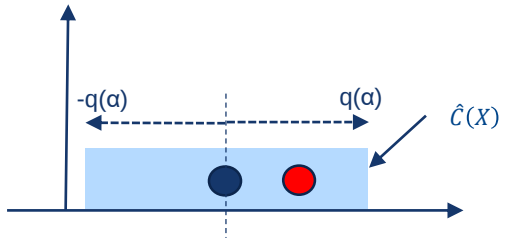
SPLIT CONFORMAL PREDICTION
TECHNICAL DETAILS (REGRESSION)

DEEL
DEpendable & Explainable Learning

2 The ***non-conformity scores*** R^i *can be defined in various ways, e.g.,*

$R^i = |\hat{y}_i - y_i|$ Lower and upper bounds

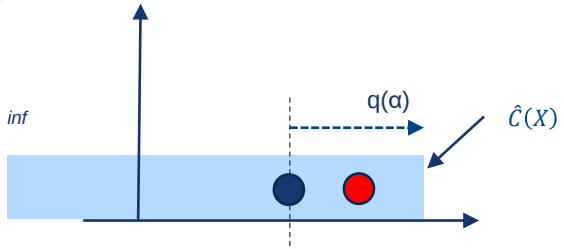
$R^i = y_i - \hat{y}_i$ (Tighter) upper bound



4 A ***prediction interval*** $\hat{C}(x)$ is built using the $\simeq 1-\alpha$ quantile $q(\alpha)$ of the R^i

$\hat{C}(x) = [\hat{y}\text{-}q(\alpha), \hat{y} + q(\alpha)]$ Lower and upper bounds

$\hat{C}(x) = (-\infty, \hat{y} + q(\alpha)]$ (Tighter) upper bound



Theoretical guarantees [1,2]

Let f be any ML model learned on a <u>training</u> set, evaluated on a <u>calibration</u> set, and later applied on some new data point (X, Y) (<u>inference</u> step). Assume that:

(i) data from all 3 datasets (training, calibration, inference) are independent;

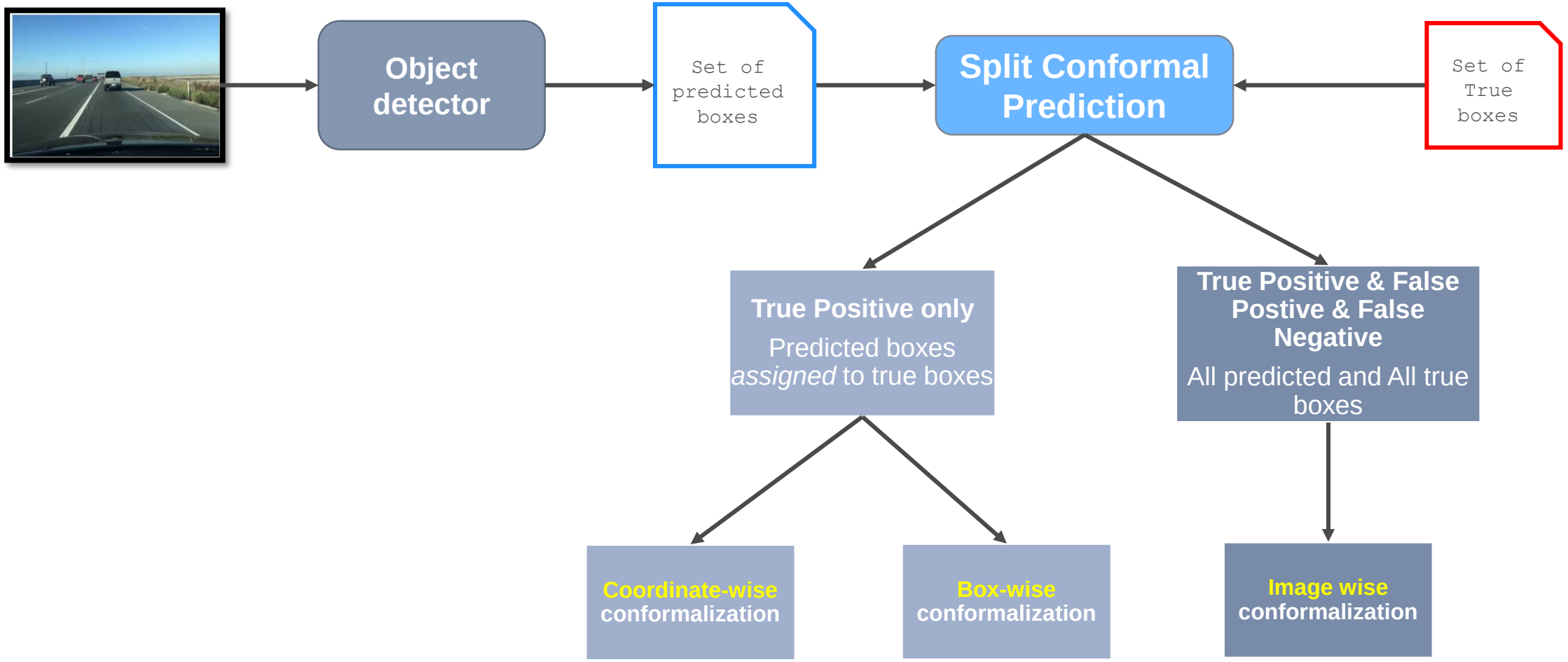
(ii) data distributions at calibration and inference steps are identical (can differ from training distribution)

Then, the prediction set $\hat{C}(X)$ at inference has the <u>desired risk level α</u> <u>on average</u>:

$$P\left(Y \in \hat{C}(X)\right) \geq 1 - \alpha$$

CONFORMAL OBJECT LOCALIZATION

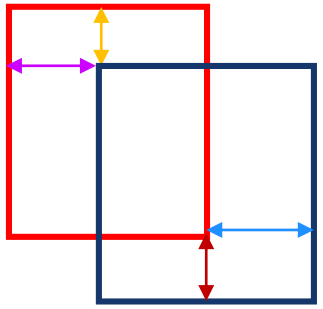
DEEL
DEpendable & Explainable Learning



Object detection with probabilistic guarantees: a conformal prediction approach *(Florence de Grancey et al.)*

CONFORMAL OBJECT LOCALIZATION: **COORDINATE-WISE** CONFORMALIZATION

- Apply Split Conformal to each bounding box **coordinate** independently
- **Objective:** *true coordinate is contained in prediction interval (risk level α)*



Ex. of non-conformity scores 2

$$R^i = \widehat{x^i_{min}} - x^i_{min},\ R^i = \widehat{y^i_{min}} - y^i_{min}$$

$$R^i = x^i_{max} - \widehat{x^i_{max}},\ R^i = y^i_{max} - \widehat{y^i_{max}}$$

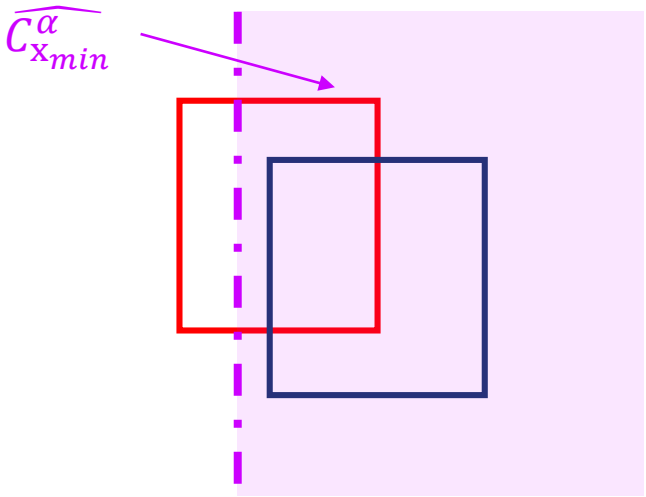
Computing prediction intervals 4

$$\widehat{C^\alpha_{x_{min}}} = [\widehat{x_{min}} - q_{xmin}(\alpha), +\infty)$$

$$\widehat{C^\alpha_{y_{min}}} = [\widehat{y_{min}} - q_{ymin}(\alpha), +\infty)$$

$$\widehat{C^\alpha_{x_{max}}} = (-\infty, \widehat{x_{max}} + q_{xmax}(\alpha)]$$

$$\widehat{C^\alpha_{y_{max}}} = (-\infty, \widehat{y_{max}} + q_{ymax}(\alpha)]$$



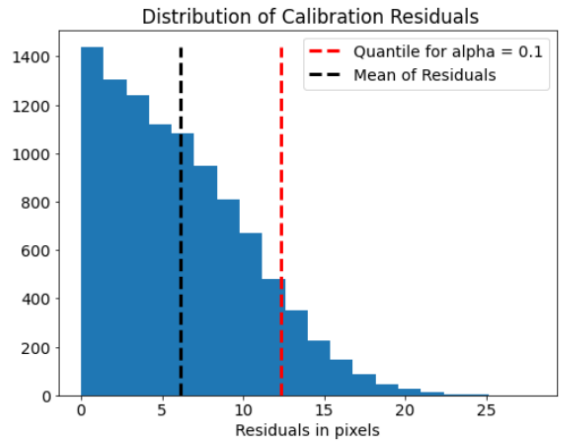
With associated guarantees

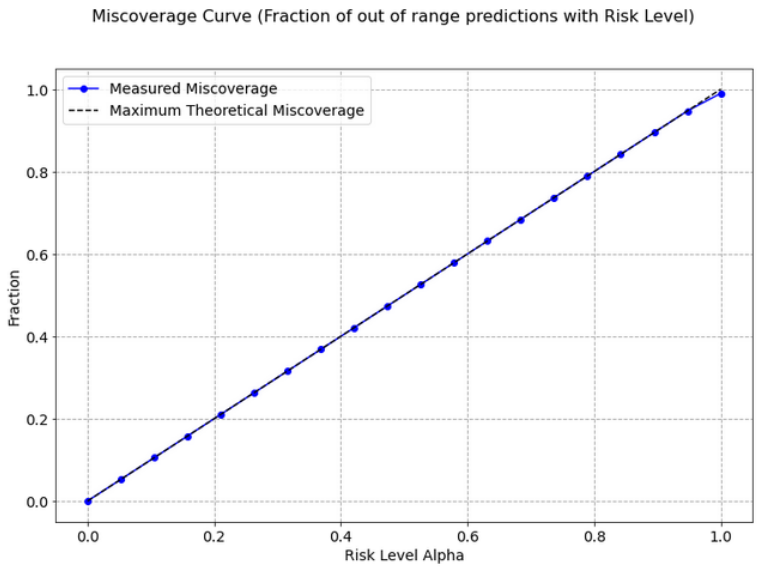
$$P(x_{min} \in \widehat{C^\alpha_{xmin}}) \geq 1 - \alpha$$

$$P(y_{min} \in \widehat{C^\alpha_{ymin}}) \geq 1 - \alpha$$

$$P(x_{max} \in \widehat{C^\alpha_{xmax}}) \geq 1 - \alpha$$

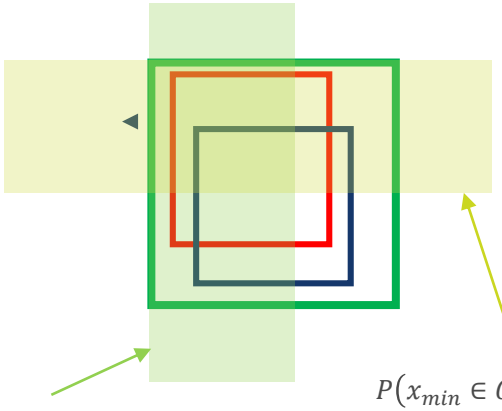
$$P(y_{max} \in \widehat{C^\alpha_{ymax}}) \geq 1 - \alpha$$





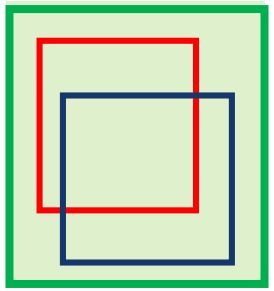
CONFORMAL OBJECT LOCALIZATION: **BOX-WISE** CONFORMALIZATION

- Apply Split Conformal to each **bounding box** independently
- **Objective**: *true box contained in conformalized box (risk level α)*
  - */!\ Coordinate-wise provides guarantees for each coordinate separately*
  - *With $\alpha = 1\%$, our method may fail to identify x_{min} / x_{max} / y_{min} / y_{max} on 1% of all boxes.*
    ⇒ At box level: one error can occur on up to 4% of all boxes.
  - *Must introduce a **multiple-testing correction such as Bonferroni correction.***



$P(x_{min} \in \widehat{C^{\alpha}_{ymin}}) \geq 1 - \alpha$

$P(y_{min} \in \widehat{C^{\alpha}_{xmin}}) \geq 1 - \alpha$

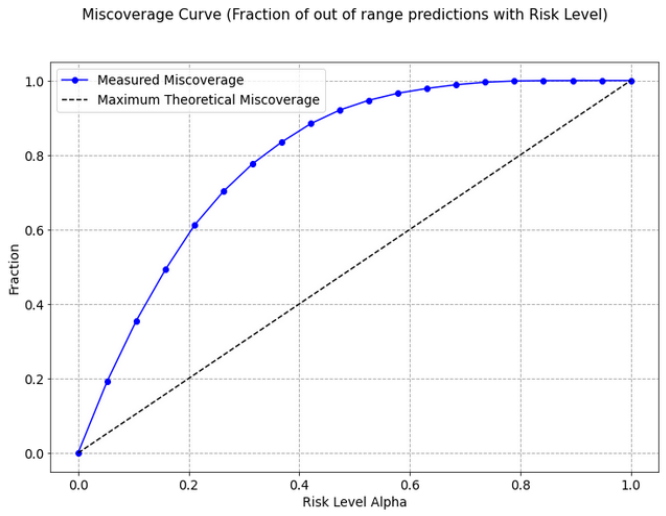


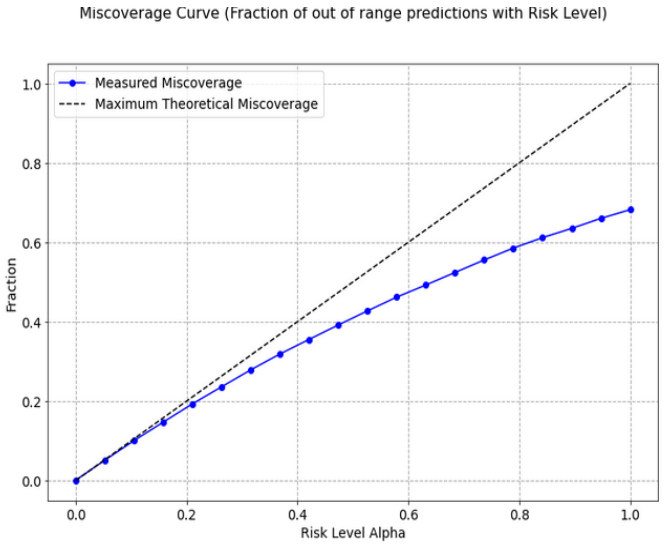
$P(x_{min} \in \widehat{C^{\alpha}_{BOX}}) \geq 1 - \boldsymbol{\alpha}$

$P(x_{min} \in \widehat{C_{xmin}}) \geq 1 - \boldsymbol{\alpha/4}$

$P(y_{min} \in \widehat{C_{ymin}}) \geq 1 - \boldsymbol{\alpha/4}$

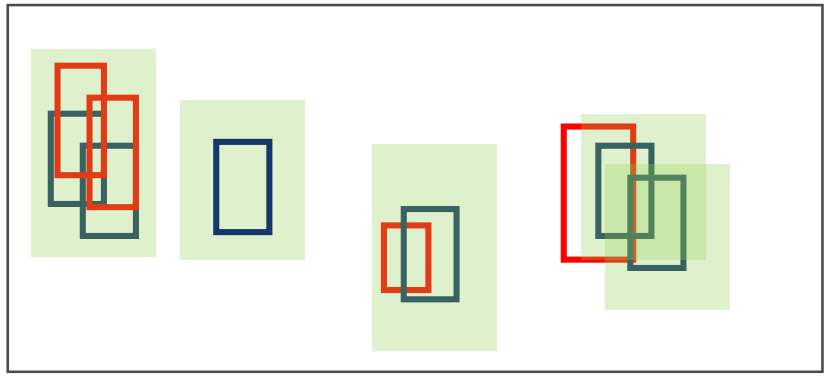
- *Bonferroni correction is equivalent to* computing conformalization for each coordinate with a risk level of $\frac{\alpha}{ncoord} = \frac{\alpha}{4}$ at step 3



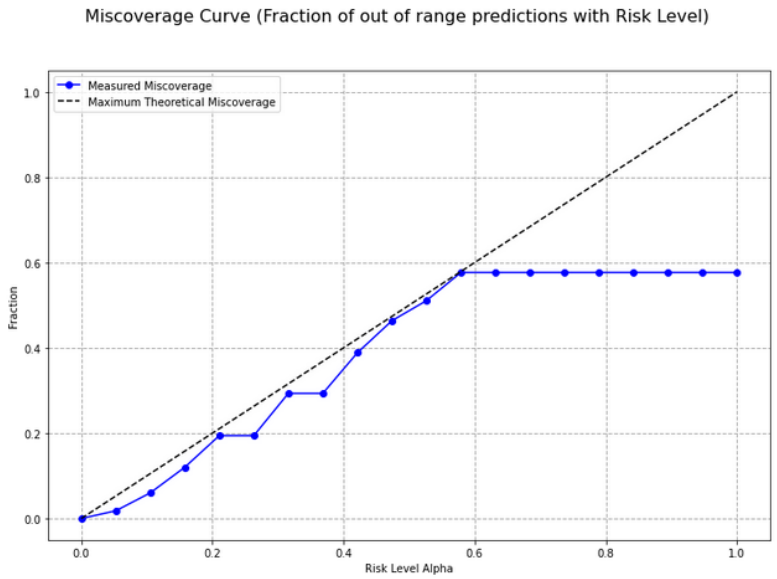


CONFORMAL OBJECT LOCALIZATION: **IMAGE-WISE** CONFORMALIZATION

- Apply Split Conformal to each **image** independently
- Objective: *set of true boxes in an image contained in prediction set (risk level α).*



$$P\left(Set\ TrueBoxes \in \widehat{C_{set\ BOX}}\right) \geq 1 - \boldsymbol{\alpha}$$

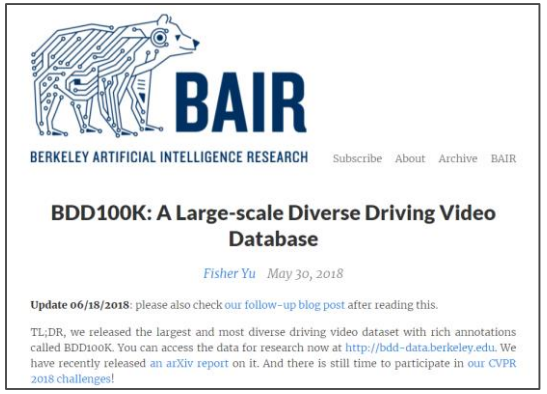


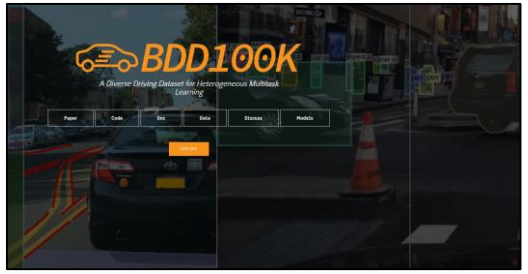
- Custom non-conformity score (step 2) at image level, such as partial or quantile **Hausdorff distance**
  - equivalent to min margin to be added to all predicted boxes to cover all true boxes
- Advantage: all true boxes are considered (instead of true positive only)
- Drawback : Conservative margins

APPLICATION TO PEDESTRIAN LOCALIZATION SETUP

DEEL
DEpendable & Explainable Learning

- Pedestrian detector
  - **Yolo V3** [1] architecture trained on Microsoft COCO
    - Detection threshold: 0.5
    - IoU threshold: 0.5 for ground truth assignment
- Dataset
  - **BDD100k Driving Data [2]**
    - Training Set used for calibration (91349 annotated persons)
    - Validation Set for evaluation (13262 annotated persons)
- Calibration parameters
  - Calibration is performed on **True Positive** detections
  - Risk level *α=0.1*





[1] Redmon, J., Farhadi, A.: YOLOv3: An incremental improvement (2018),arXiv:1804.02767
[2] Yu, F., Xian, W., Chen, Y., Liu, F., Liao, M., Madhavan, V., Darrell, T.:BDD100K: a diverse driving dataset for heterogeneous multitask learning (2018),arXiv:1805.04687

APPLICATION TO PEDESTRIAN LOCALIZATION
BOX-WISE VS COORDINATE-WISE MARGINS

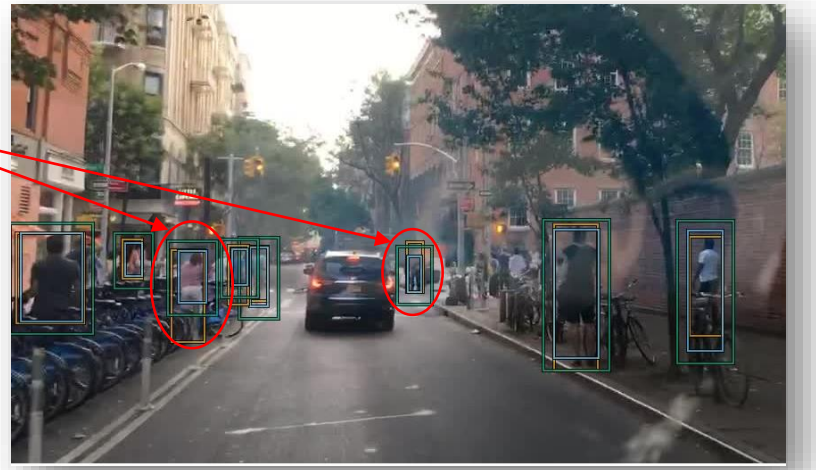
DEEL
DEpendable & Explainable Learning

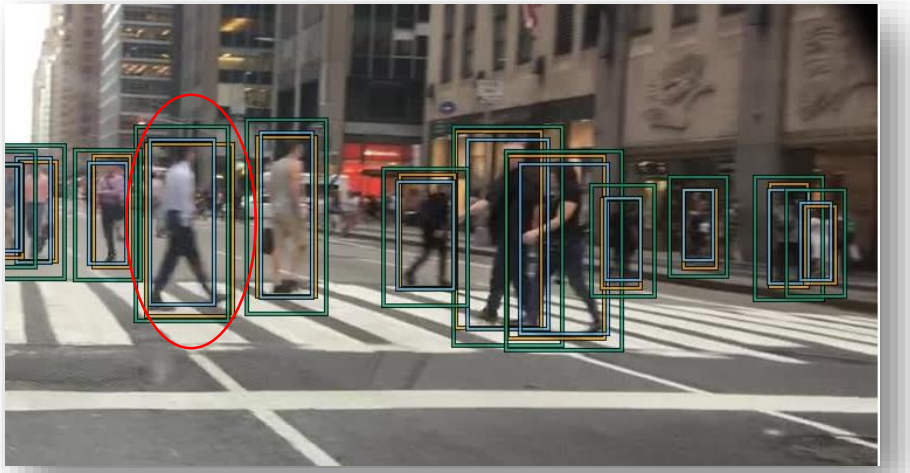
Object detection with probabilistic guarantees: a conformal prediction approach *(Florence de Grancey et al.)*

APPLICATION TO PEDESTRIAN LOCALIZATION
BOX-WISE CONFORMALIZATION

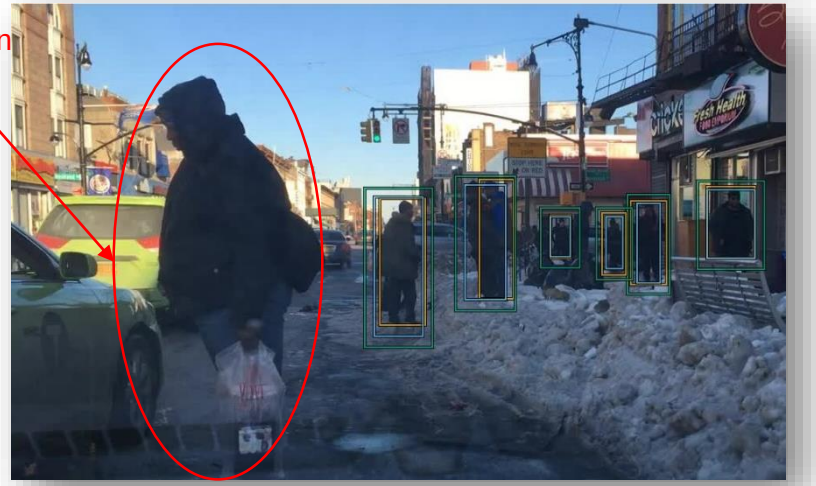
DEEL
DEpendable & Explainable Learning

Out of prediction set examples

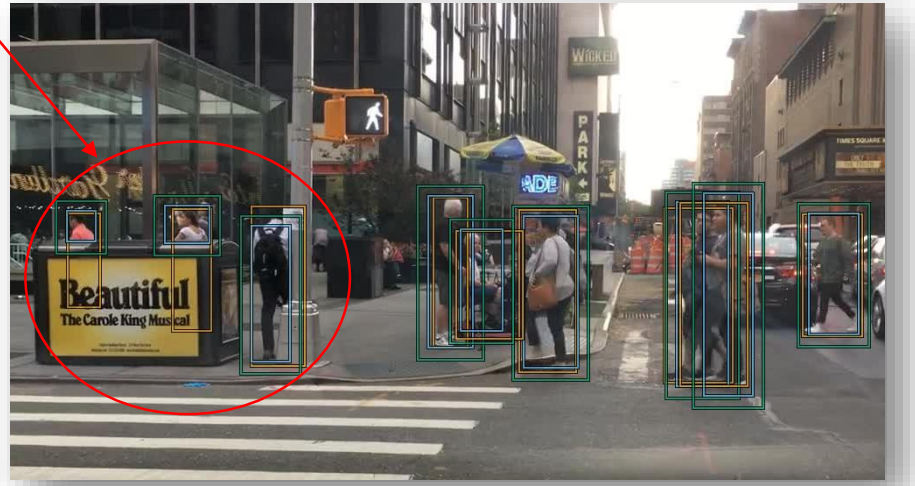




False negative: no conformalization



Out of prediction set : Ground Truth errors identification



Object detection with probabilistic guarantees: a conformal prediction approach *(Florence de Grancey et al.)*

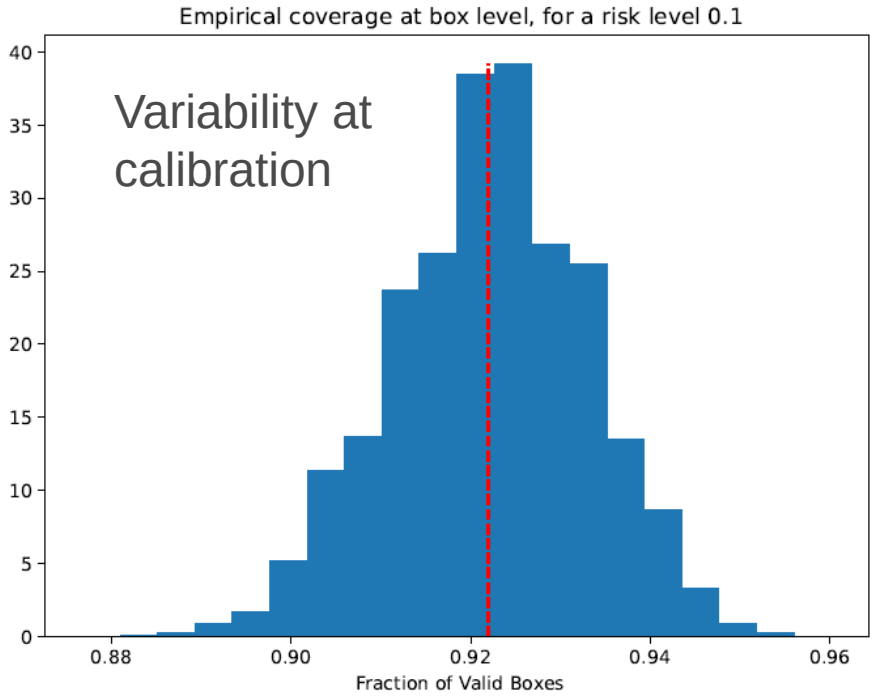
STATISTICAL PITFALLS

DEEL
DEpendable & Explainable Learning

The probabilistic guarantees obtained from Conformal Prediction methods are subject to several **statistical pitfalls and** must be **carefully interpreted**!

- **Guarantees are "on average"** over calibration and test sets

- Data requirements: (i) **independence** (ii) **same distribution** for calibration and inference data.



CONCLUSION & FUTURE WORK

DEEL
DEpendable & Explainable Learning

Conclusions

- **Probabilistic guarantees** for object localization at various levels:
  - Coordinate
  - Bounding box
  - Image
- Demonstration on a **pedestrian detection** use-case.
- Focus on several **statistical pitfalls**

Future work

- Address the **full object detection problem**
- Study **link** between **probabilistic guarantees** and **safety-related risks** at system-level
- Analyze other **non-conformity scores**

https://www.deel.ai/

THANK YOU FOR YOUR ATTENTION

https://www.deel.ai/

DEEL
DEpendable & Explainable Learning

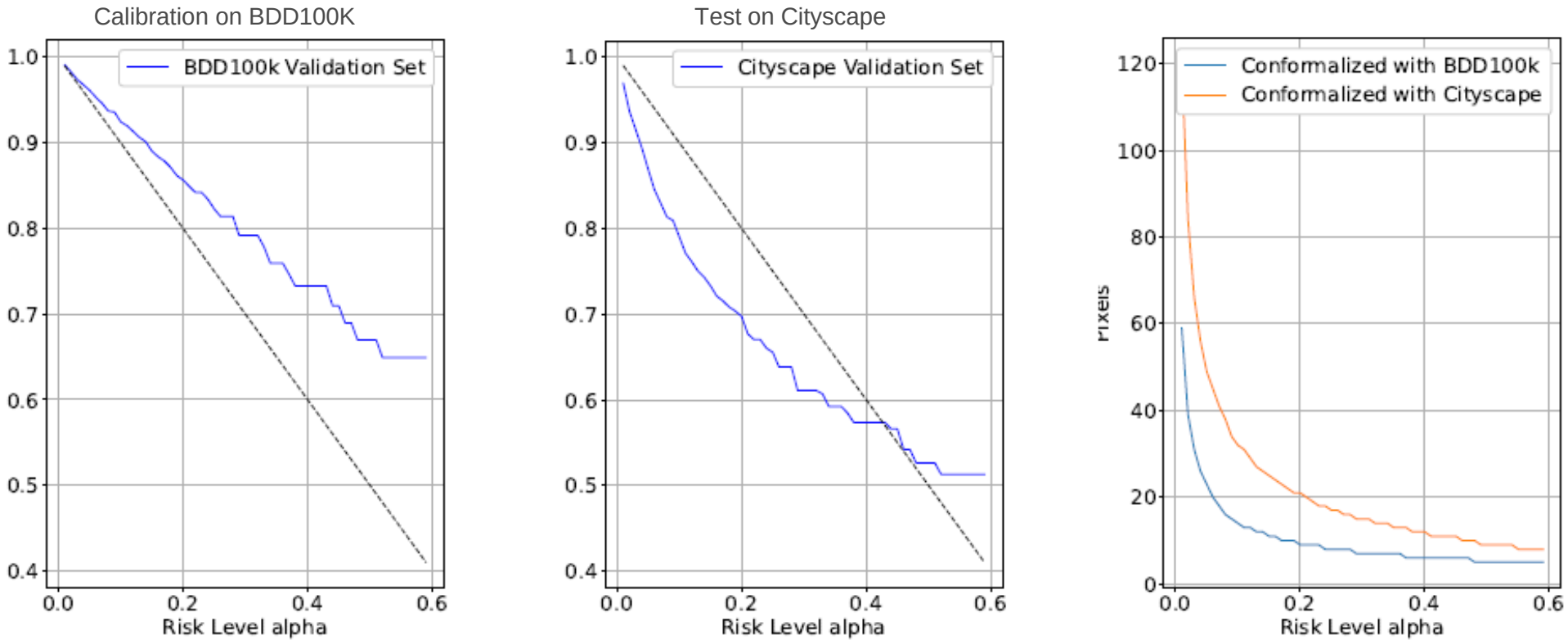
APPENDIX

IVADO SAINT EXUPÉRY CRIAQ ANITI ARTIFICIAL & NATURAL INTELLIGENCE TOULOUSE INSTITUTE

STATISTICAL PITFALLS

DEEL
DEpendable & Explainable Learning

Data samples used for calibration and inference must **belong to the same data distribution**



Object detection with probabilistic guarantees: a conformal prediction approach *(Florence de Grancey et al.)*

DEEL
DEpendable & Explainable Learning

THANK YOU FOR YOUR ATTENTION

IVADO
IRT SAINT EXUPÉRY
CRIAQ
ANITI
ARTIFICIAL & NATURAL INTELLIGENCE TOULOUSE INSTITUTE