

SplatPlanner: Efficient Autonomous Exploration via Permutohedral Frontier Filtering

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Context



Micro Aerial Vehicle (MAV):

- + Agility
- + Form factor
- + Affordability

Limitations:

- Battery-life
- On-board compute
- Online runtime

Autonomous Exploration:

-  Using Depth+Odometry sensors
-  No prior knowledge of the scene



Context



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Autonomous Exploration:

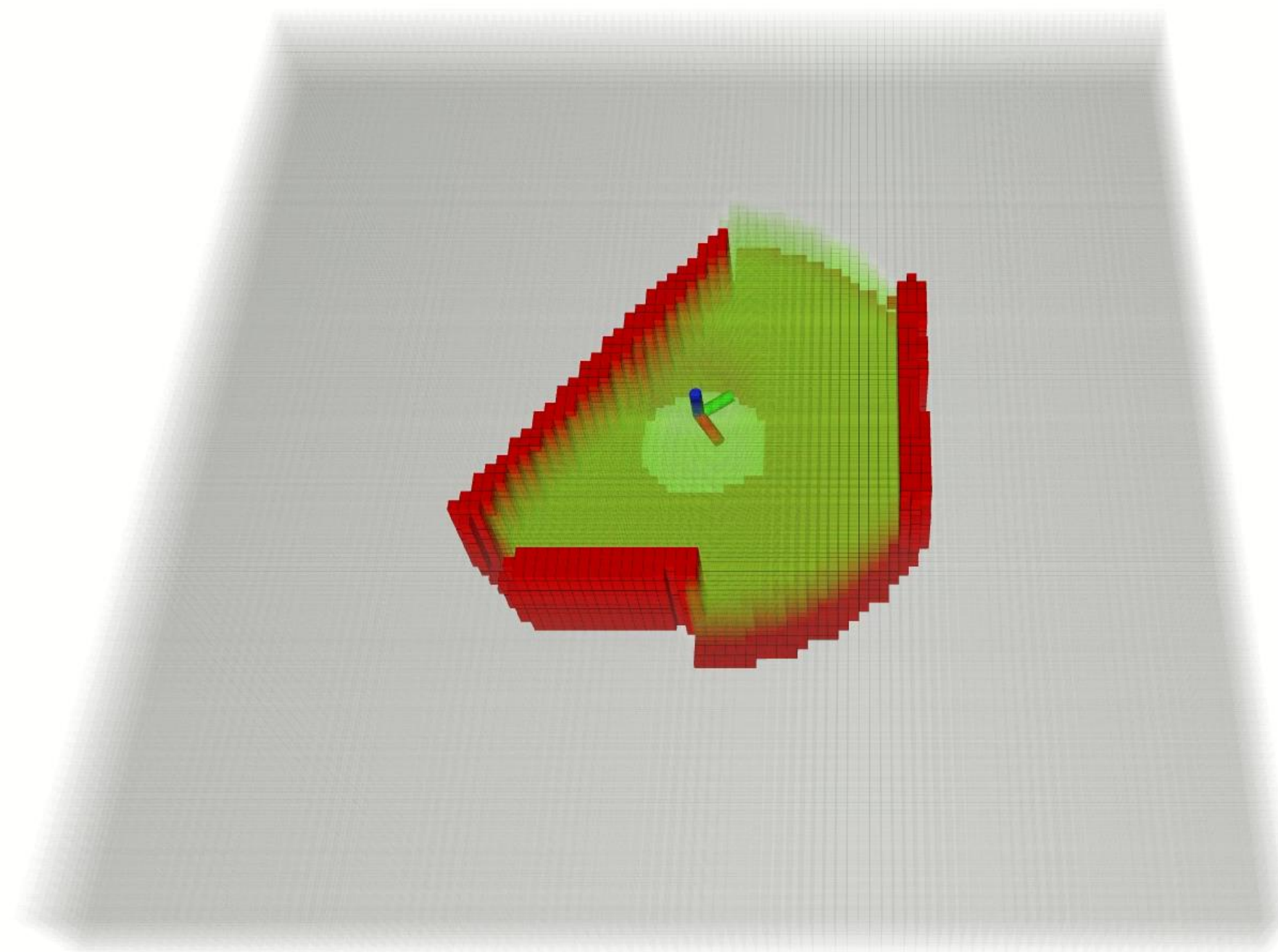
-  Using Depth+Odometry sensors
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Voxel labeling

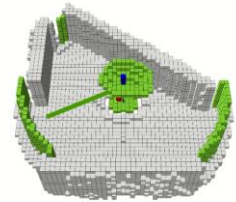
-  Empty
-  Occupied
-  Unknown

 **Goal:** Maximize volumetric efficiency

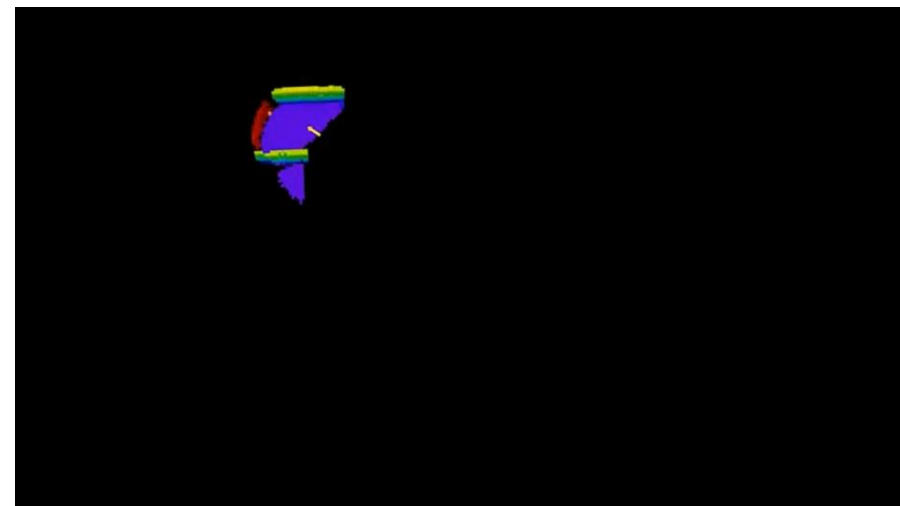


Prior Work

Frontier based

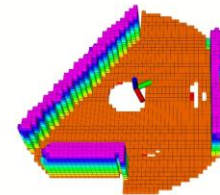


Yamauchi, CIRA 1997 [1]



Cieslewski *et al.*, IROS 2017 [2]

Sampling based

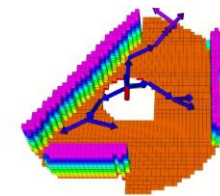


Bircher *et al.*, ICRA 2016 [3]

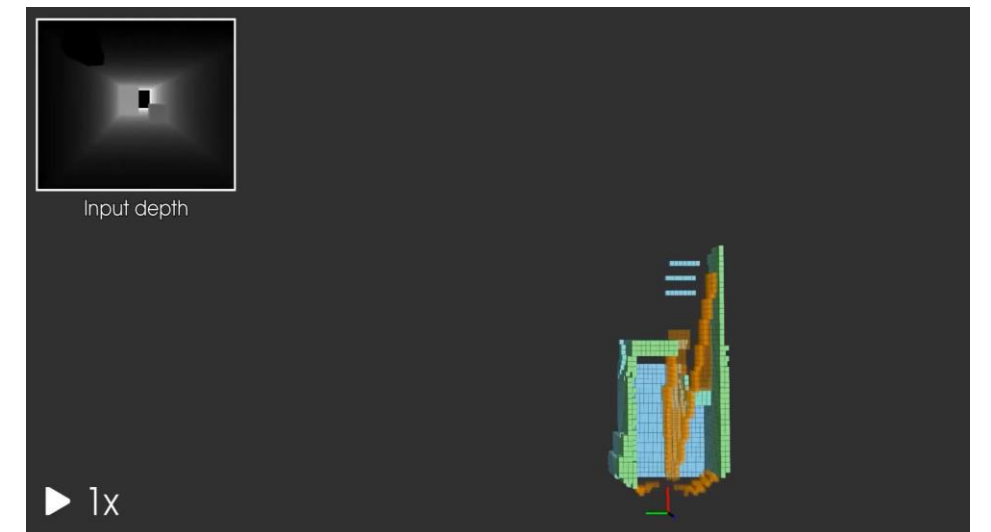


Schmid *et al.*, RAL 2020 [4]

Hybrid methods



Selin *et al.*, RAL 2019 [5]



Dai *et al.*, ICRA 2020 [6]

[1] Yamauchi, Brian. "A frontier-based approach for autonomous exploration.", [IEEE CIRA'97](#).

[2] Cieslewski, Titus, *et al.* "Rapid exploration with multi-rotors: A frontier selection method for high-speed flight.", [IEEE IROS 2017](#).

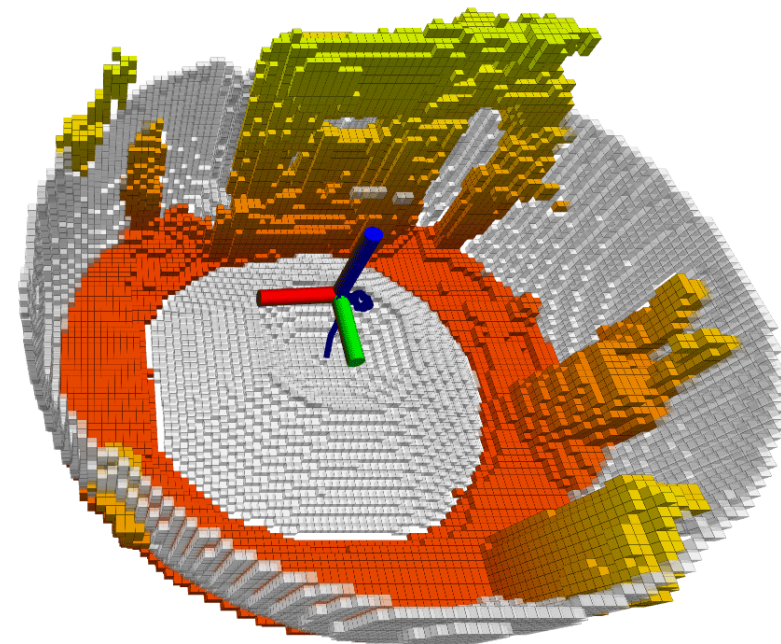
[3] Bircher, Andreas, *et al.* "Receding horizon" next-best-view" planner for 3d exploration.", [IEEE ICRA 2016](#).

[4] Schmid, Lukas, *et al.* "An Efficient Sampling-based Method for Online Informative Path Planning in Unknown Environments.", [IEEE RAL 2020](#).

[5] Selin, Magnus, *et al.* "Efficient autonomous exploration planning of large-scale 3-D environments.", [IEEE RAL, 2019](#).

[6] Dai, Anna, *et al.* "Fast Frontier-based Information-driven Autonomous Exploration with an MAV.", [IEEE ICRA 2020](#).

SplatPlanner



01

End-to-end hybrid system for autonomous exploration

02

Uses highly efficient Bilateral Filtering to guide the exploration

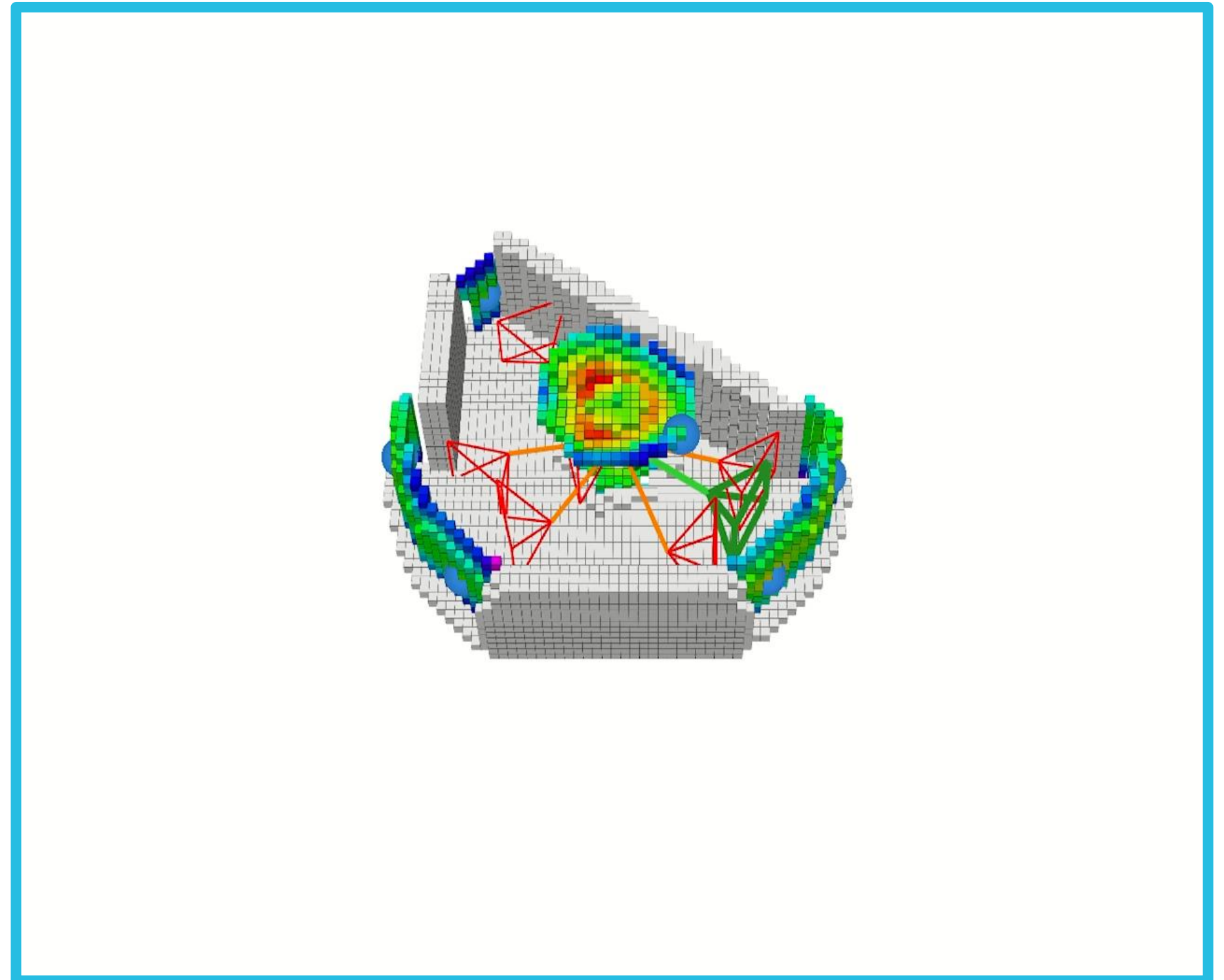
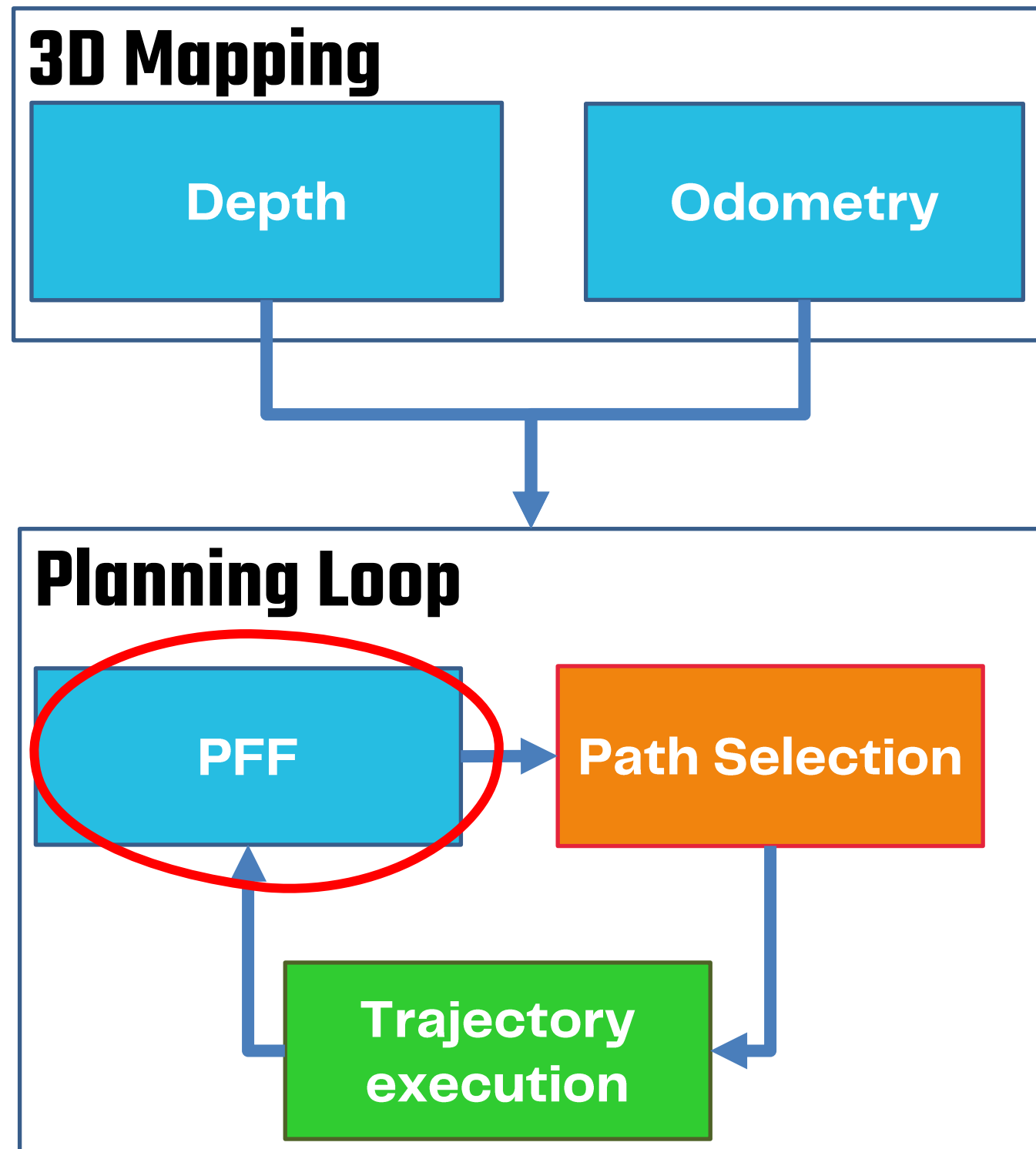
03

Outperforms *State-of-the-art* on challenging benchmarks

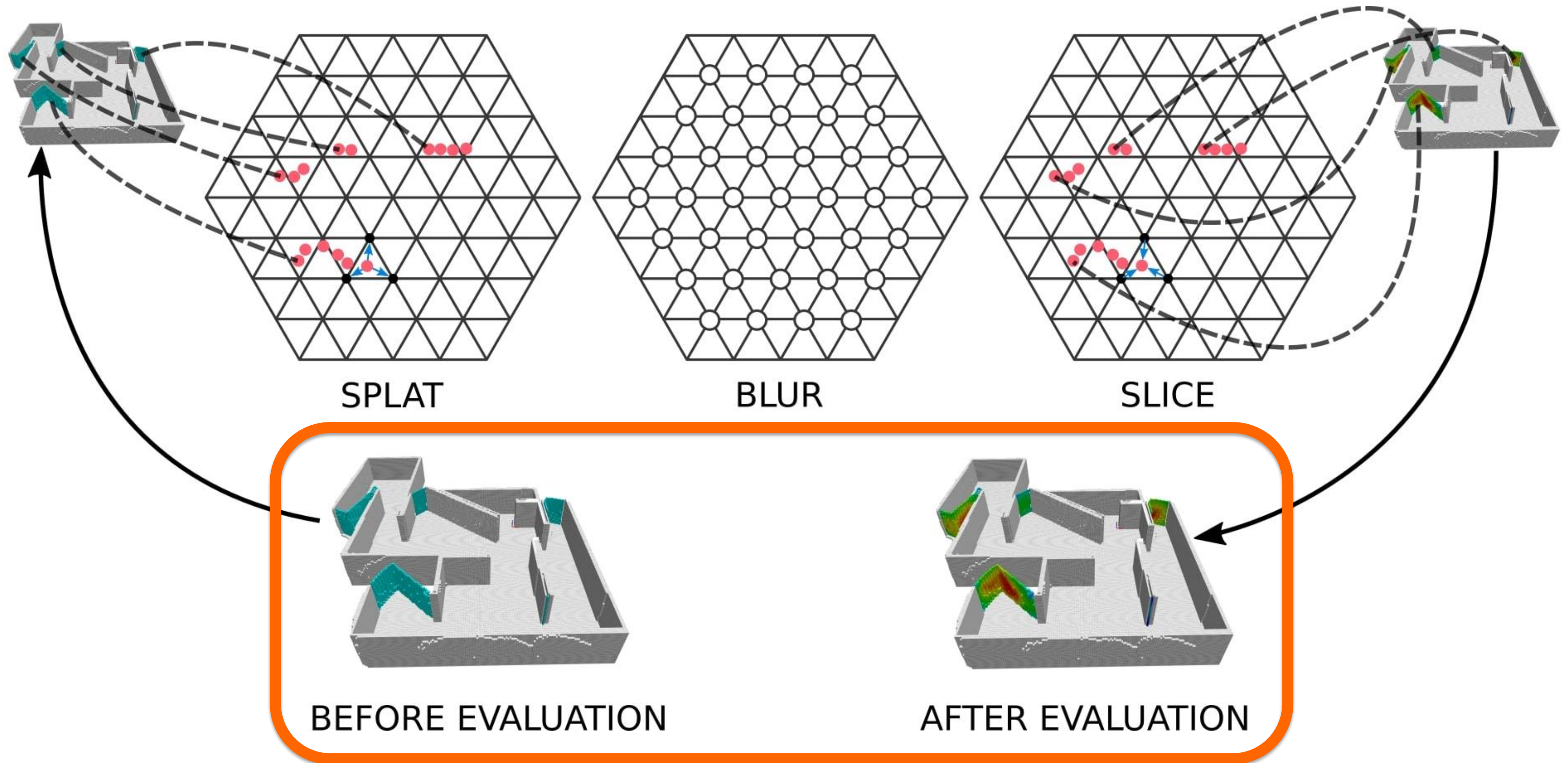
04

Real flight capabilities

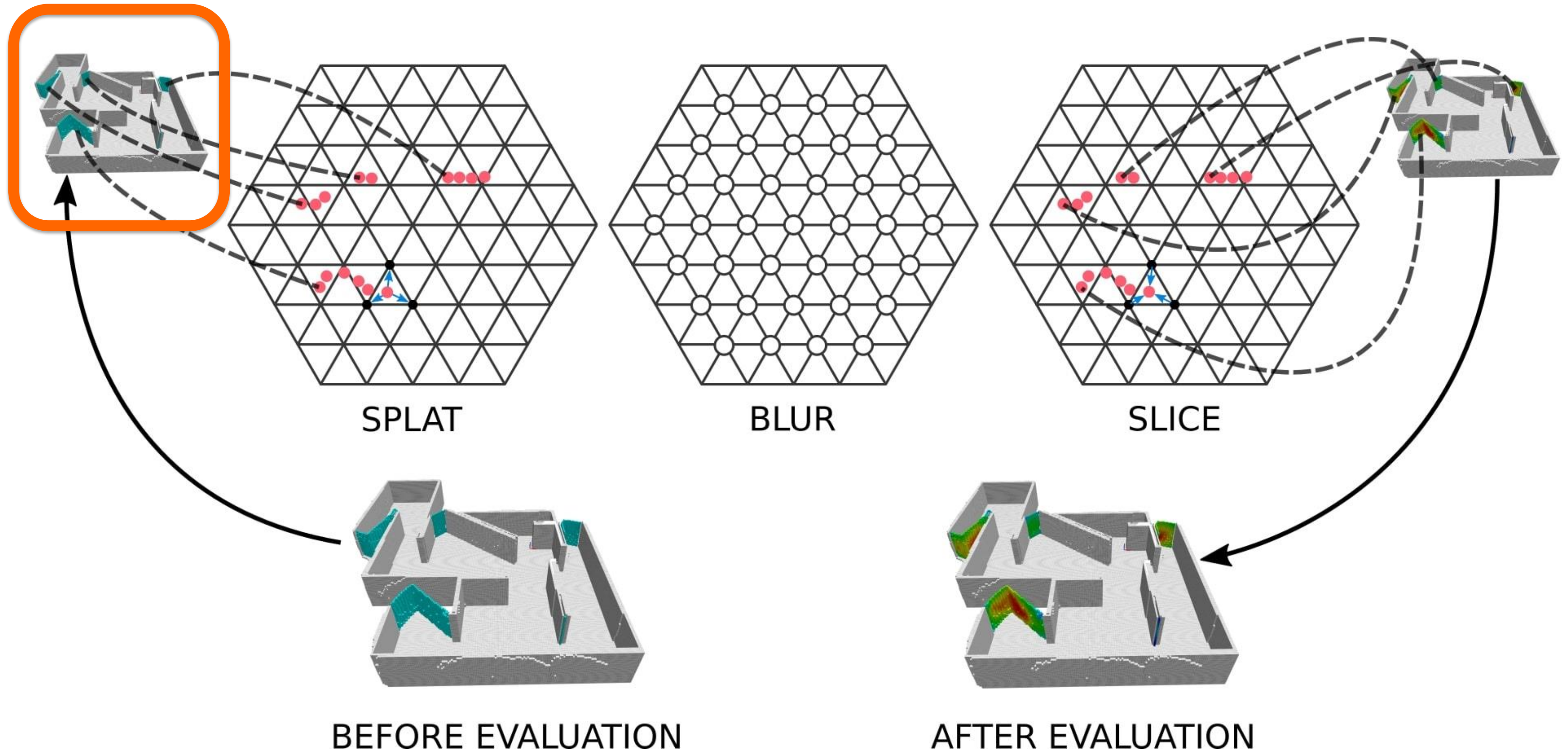
System Overview



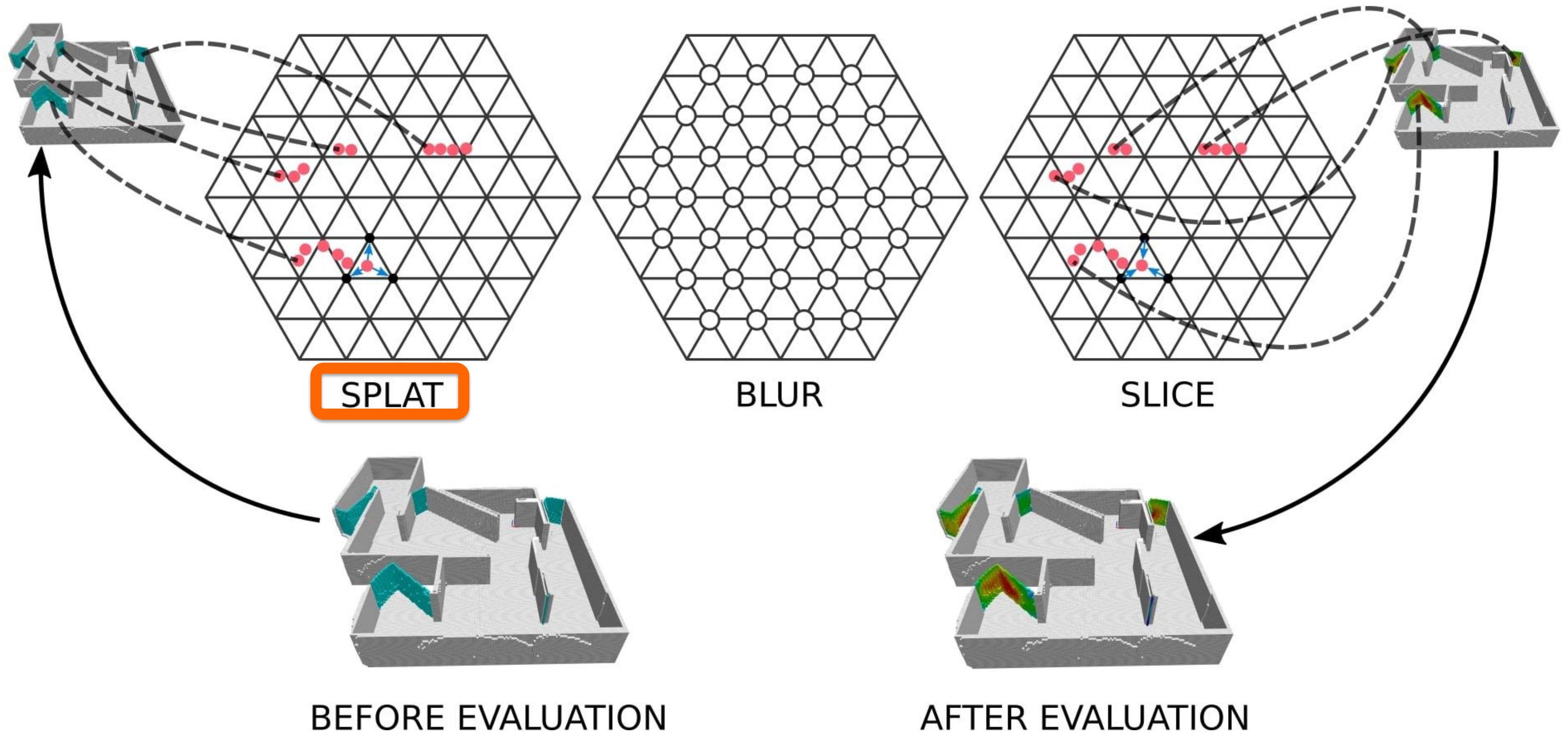
Permutohedral Frontier Filtering (PFF)



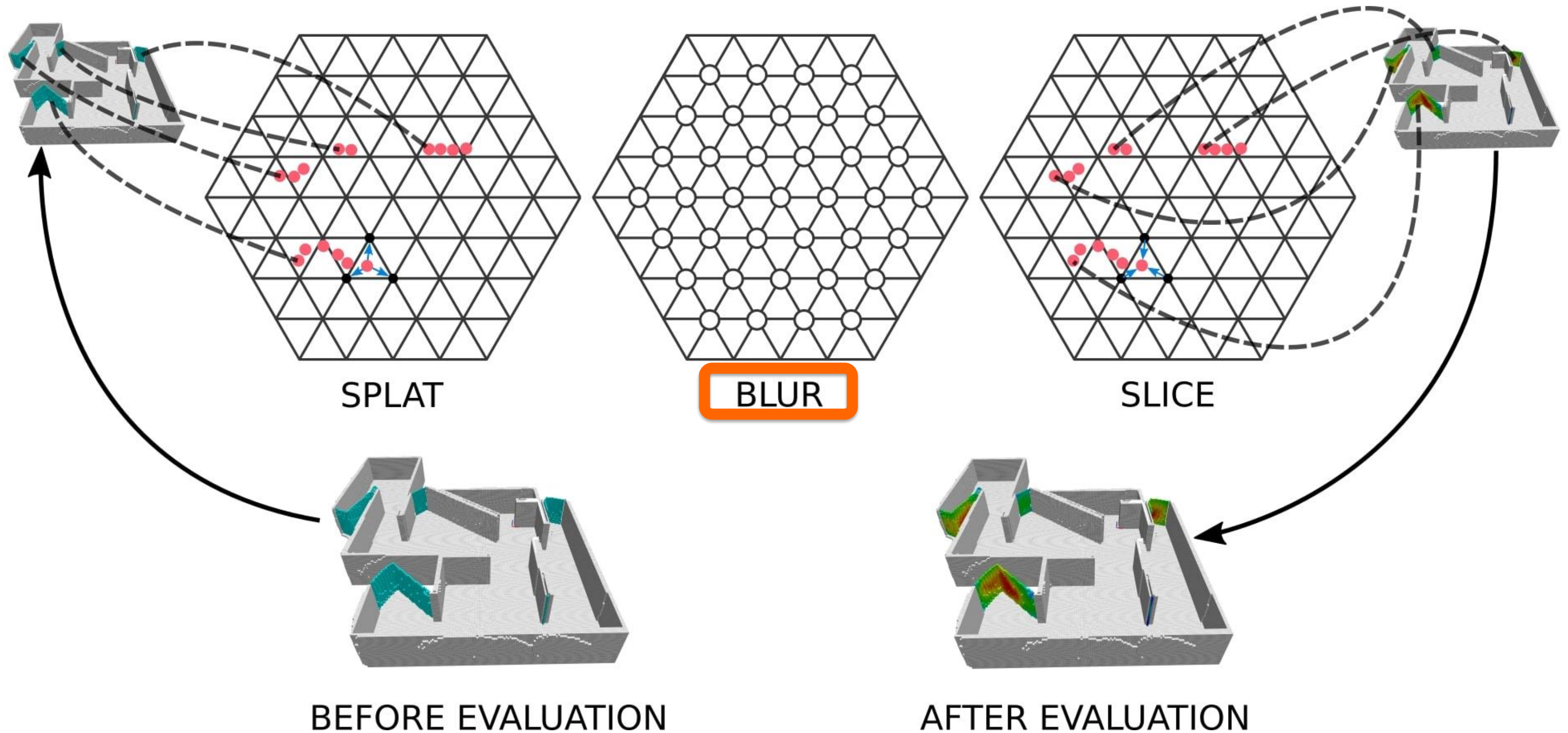
Permutohedral Frontier Filtering (PFF)



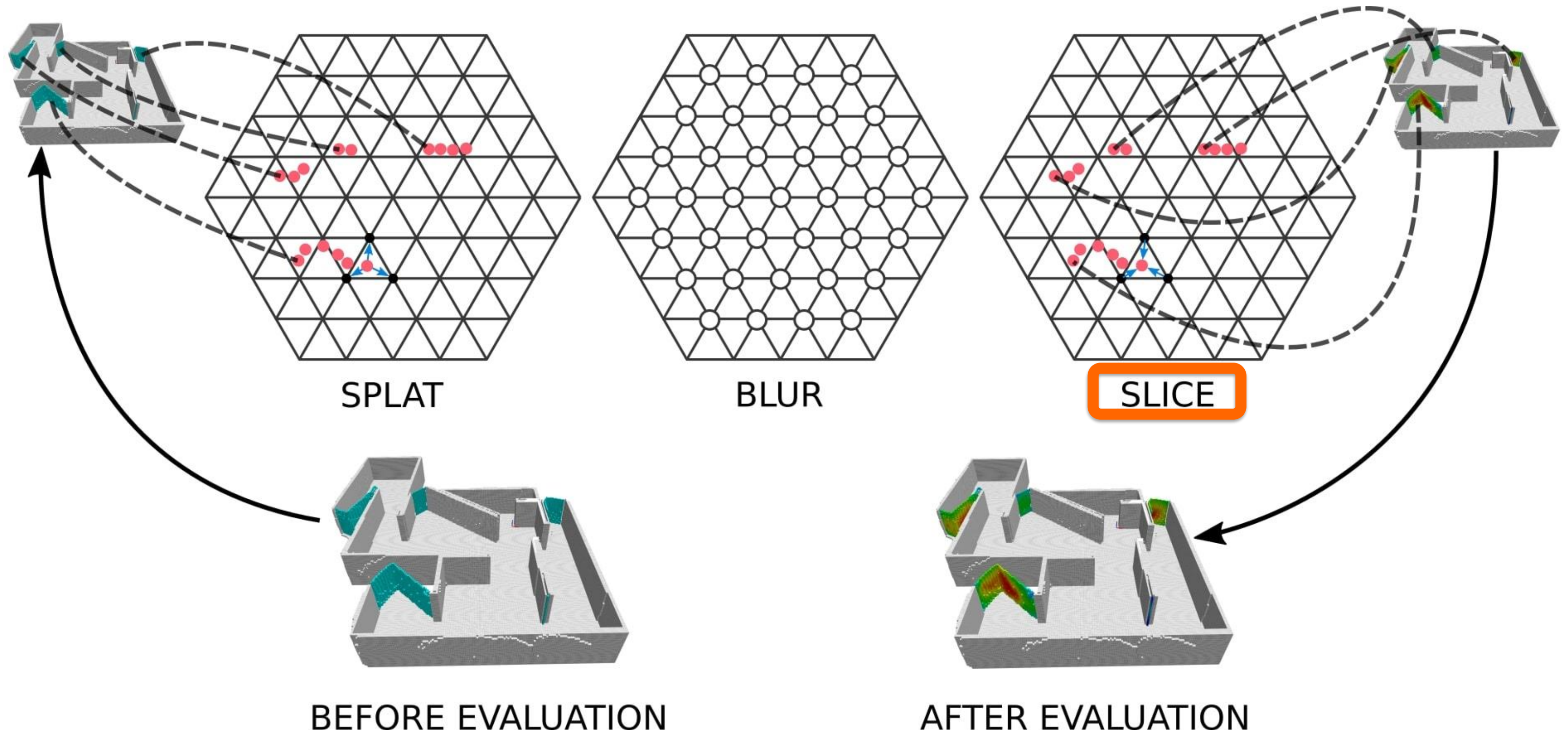
Permutohedral Frontier Filtering (PFF)



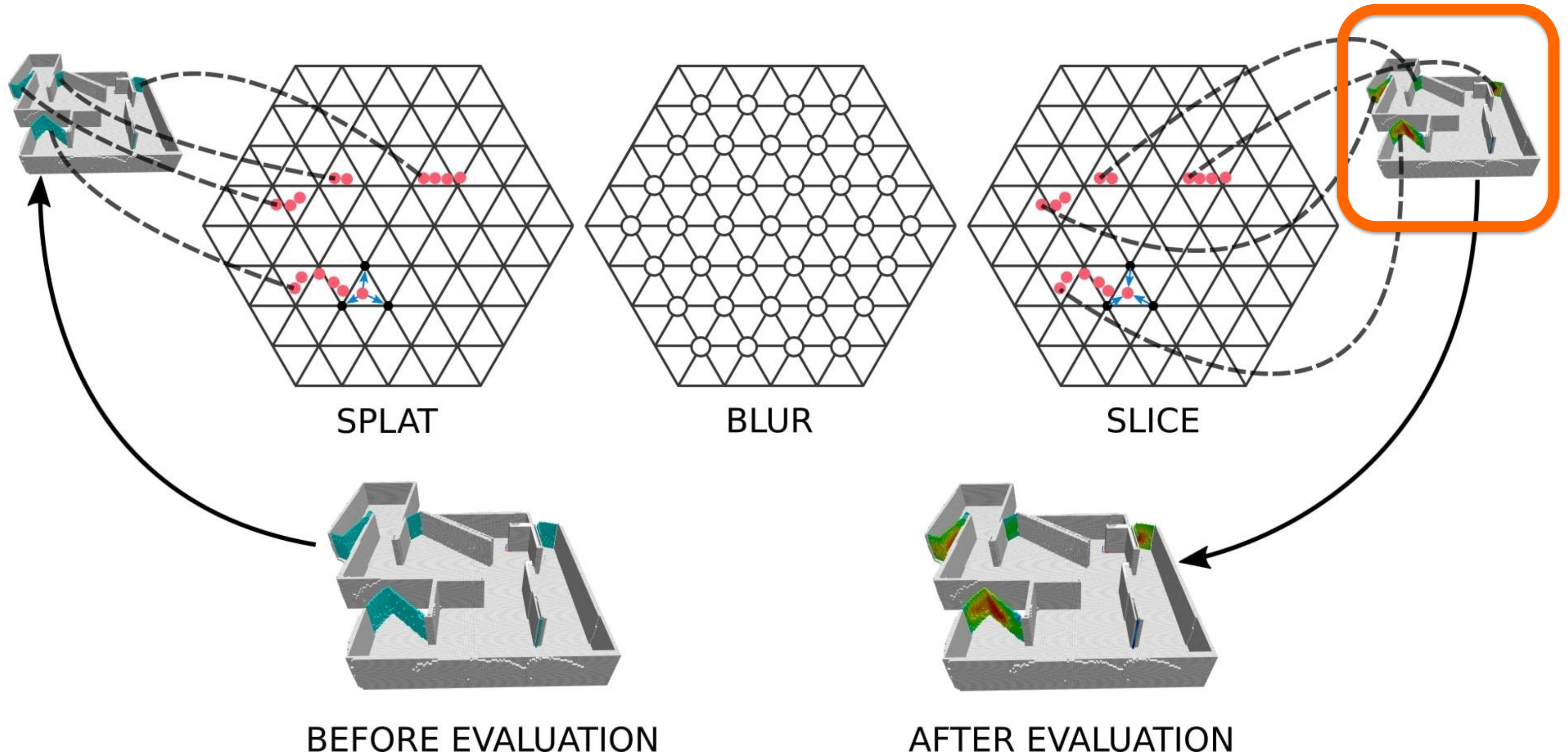
Permutohedral Frontier Filtering (PFF)



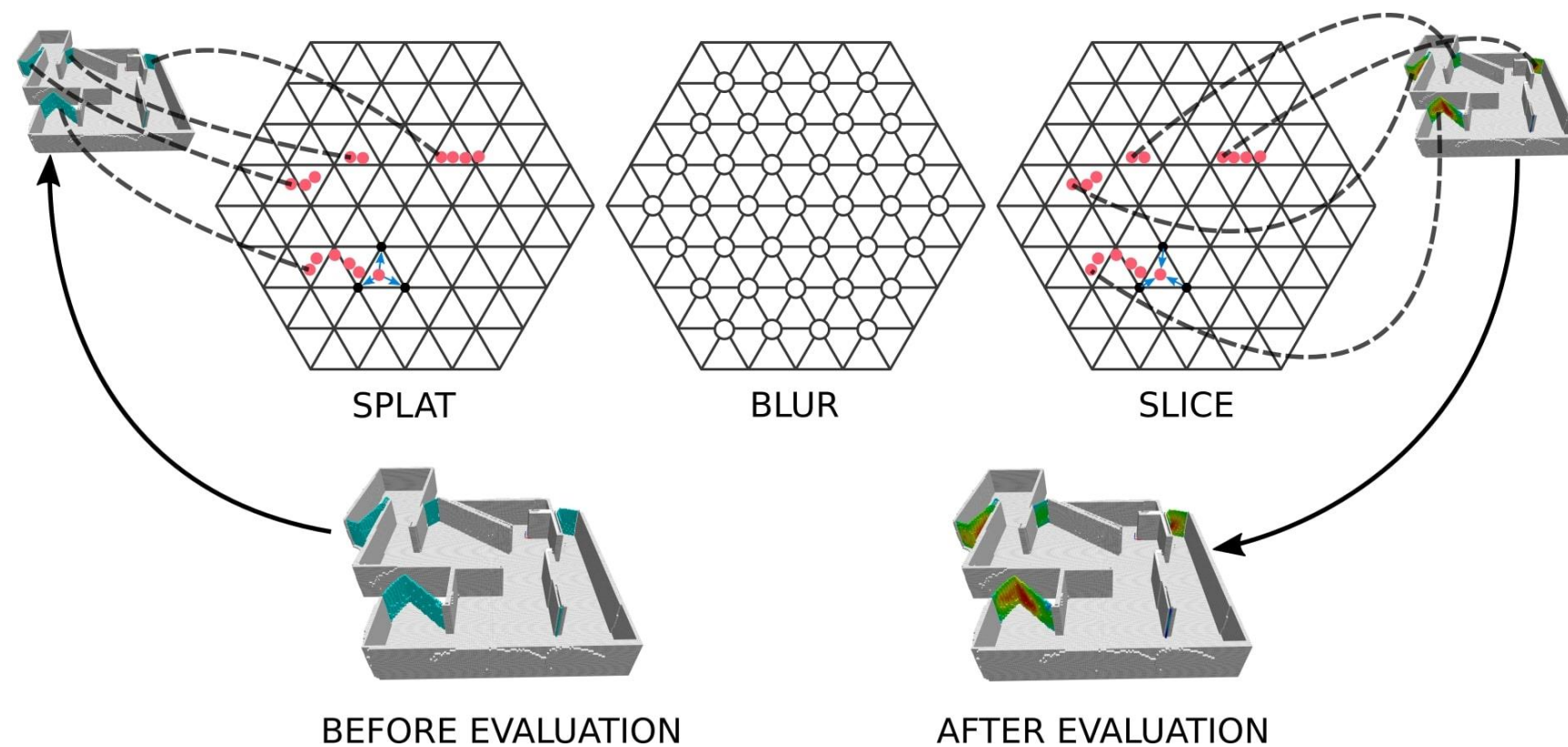
Permutohedral Frontier Filtering (PFF)



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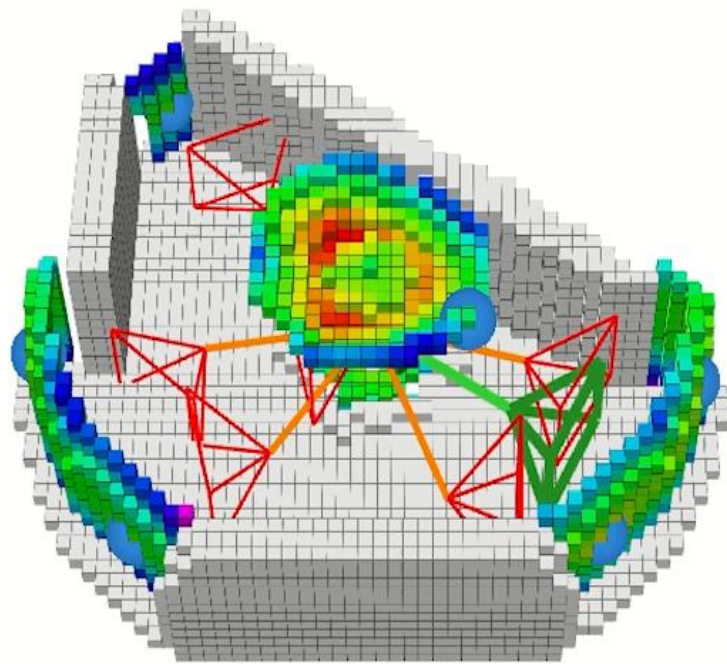


PFF – Advantages



- ✈ **Splat**, **Blur** and **Slice** are **linear** in input size
- ✈ The **Blur** operation induces an **implicit spatial grouping** of frontiers
- ✈ Requires **one single parameter** (scaling matrix)
- ✈ Allows **arbitrary number of features**

Path Selection Routine



01 **Extraction** of goal candidate and sampled paths using RRT* [1]

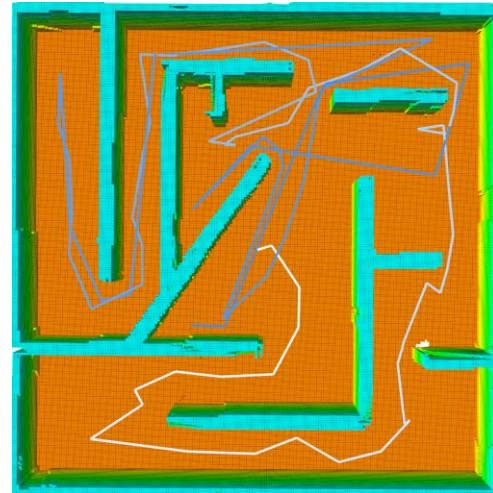
02 **View evaluation**, by maximizing:

$$g(P_i, \mu_i) = \frac{u(\mu_i)}{T(P_i)}$$

03 **Execution** of the most promising path amongst candidates P_i

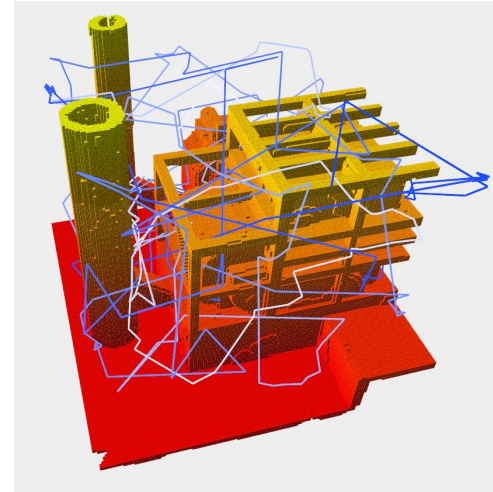
Results

Maze



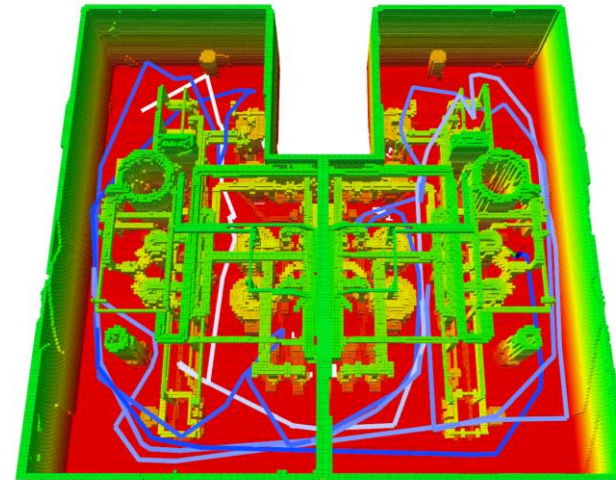
Handcrafted scene (400m²)
20m x 20m x 2.5m

Powerplant



Large outdoor (1000m²)
33m x 31m x 26m

Facility



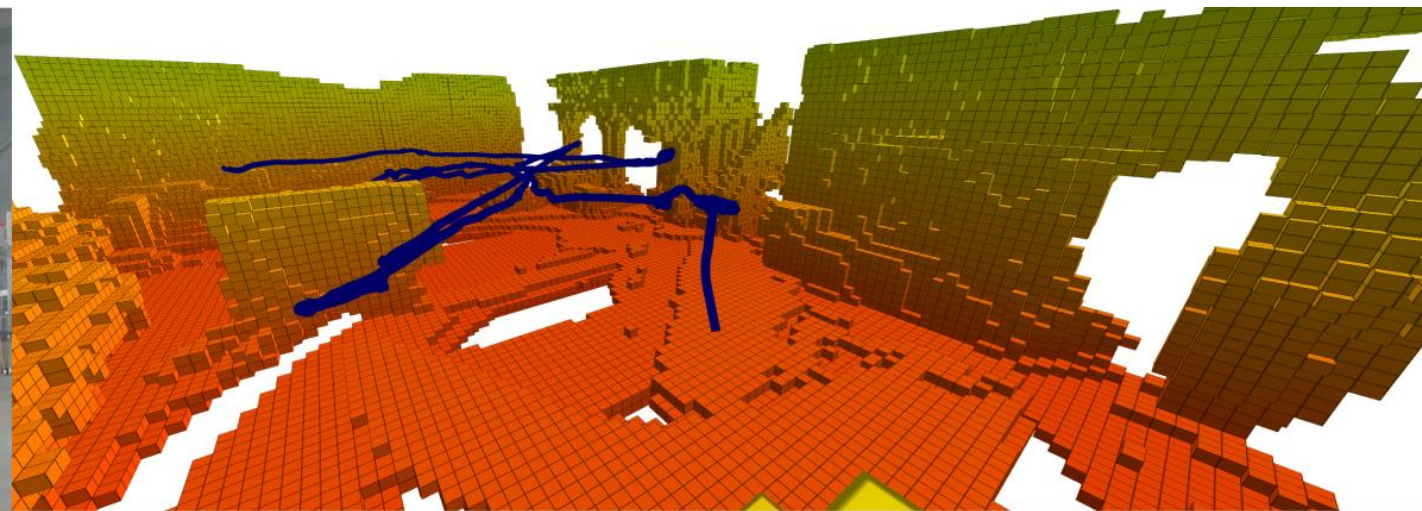
Complex industrial (300m²)
18.5m x 17.5m x 4.6m

1 Comparative Experiments

- Simulation testbed (RotorS/Gazebo)
- Methods:
 - SplatPlanner (ours)
 - AEP, RAL 2019 [1]
 - ESM, RAL 2020 [2]
 - FFI, ICRA 2020 [3]
- Evaluation criterion: Explored volume / time

2 Real Flight Scenario

- Large Warehouse environment
- 150m²

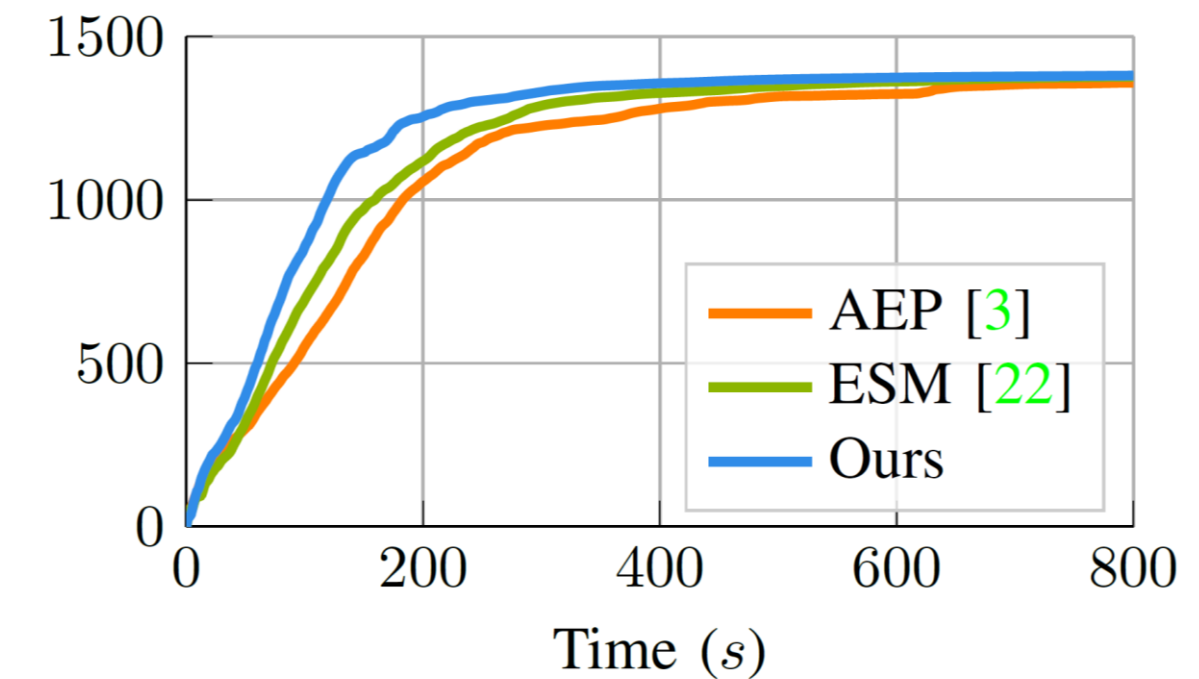
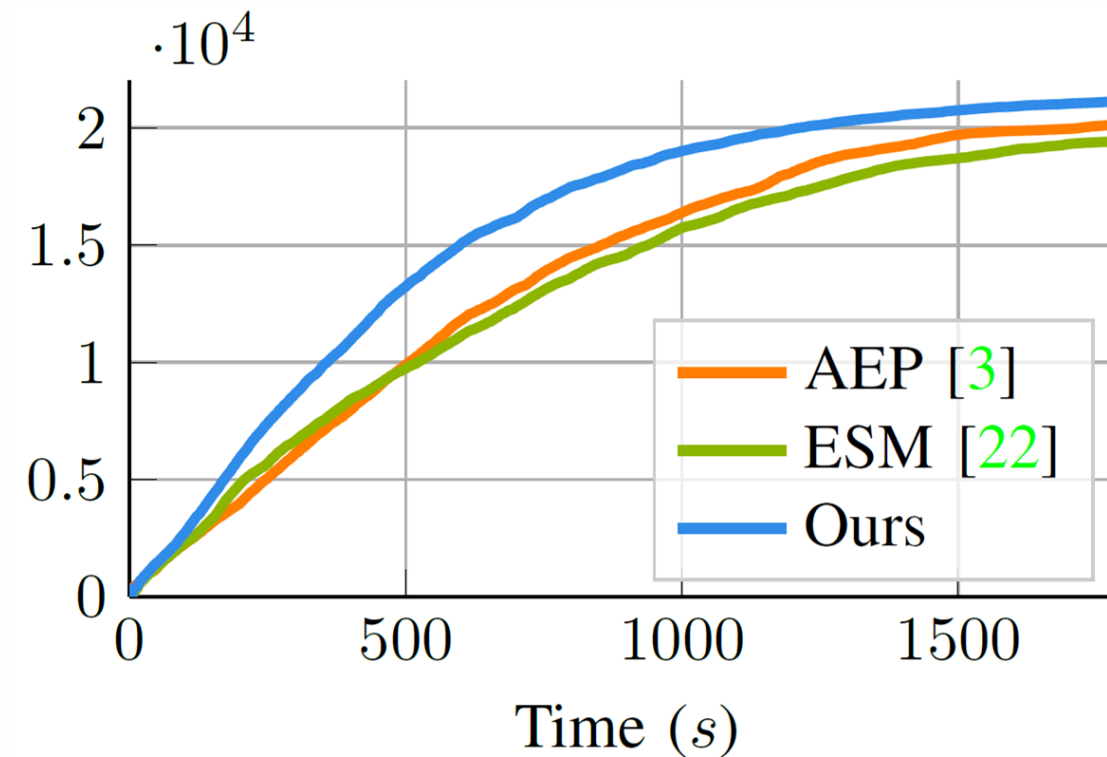
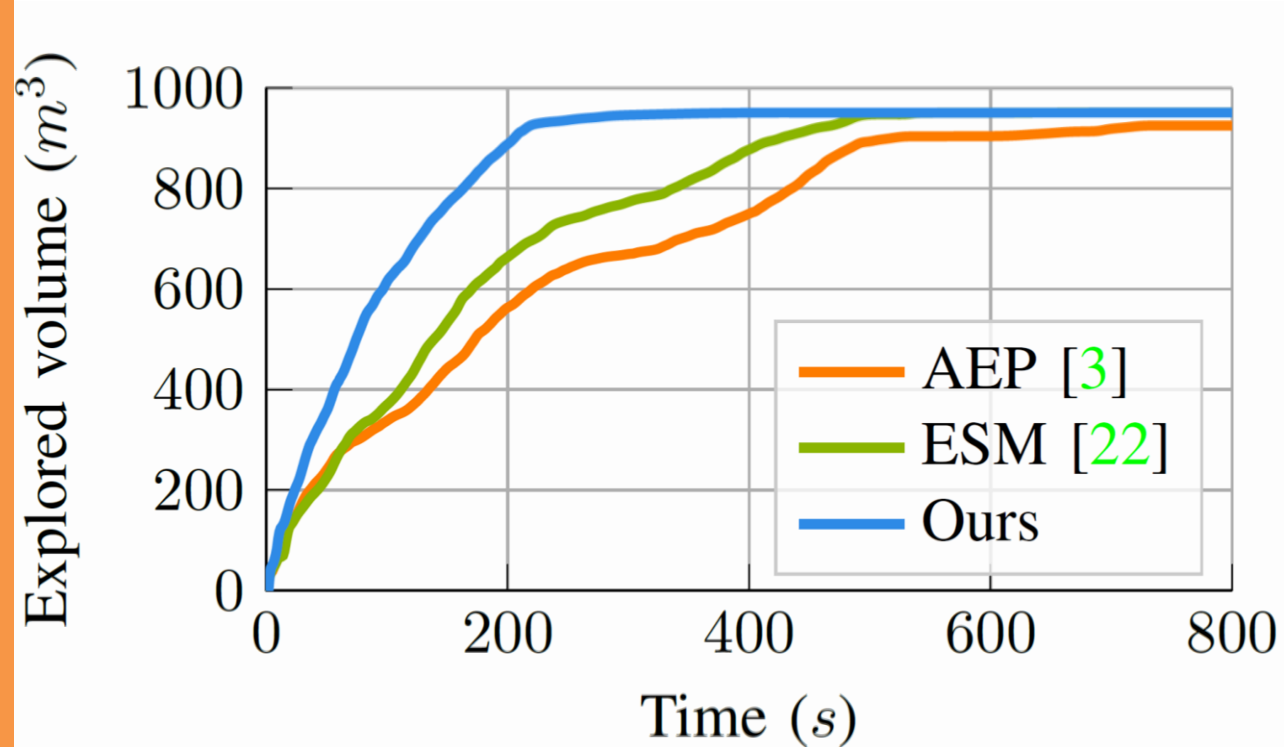


[1] Selin, Magnus, *et al.* "Efficient autonomous exploration planning of large-scale 3-D environments.", *IEEE RAL 2019*.

[2] Schmid, Lukas, *et al.* "An Efficient Sampling-based Method for Online Informative Path Planning in Unknown Environments.", *IEEE RAL 2020*.

[3] Dai, Anna, *et al.* "Fast Frontier-based Information-driven Autonomous Exploration with an MAV.", *IEEE ICRA 2020*.

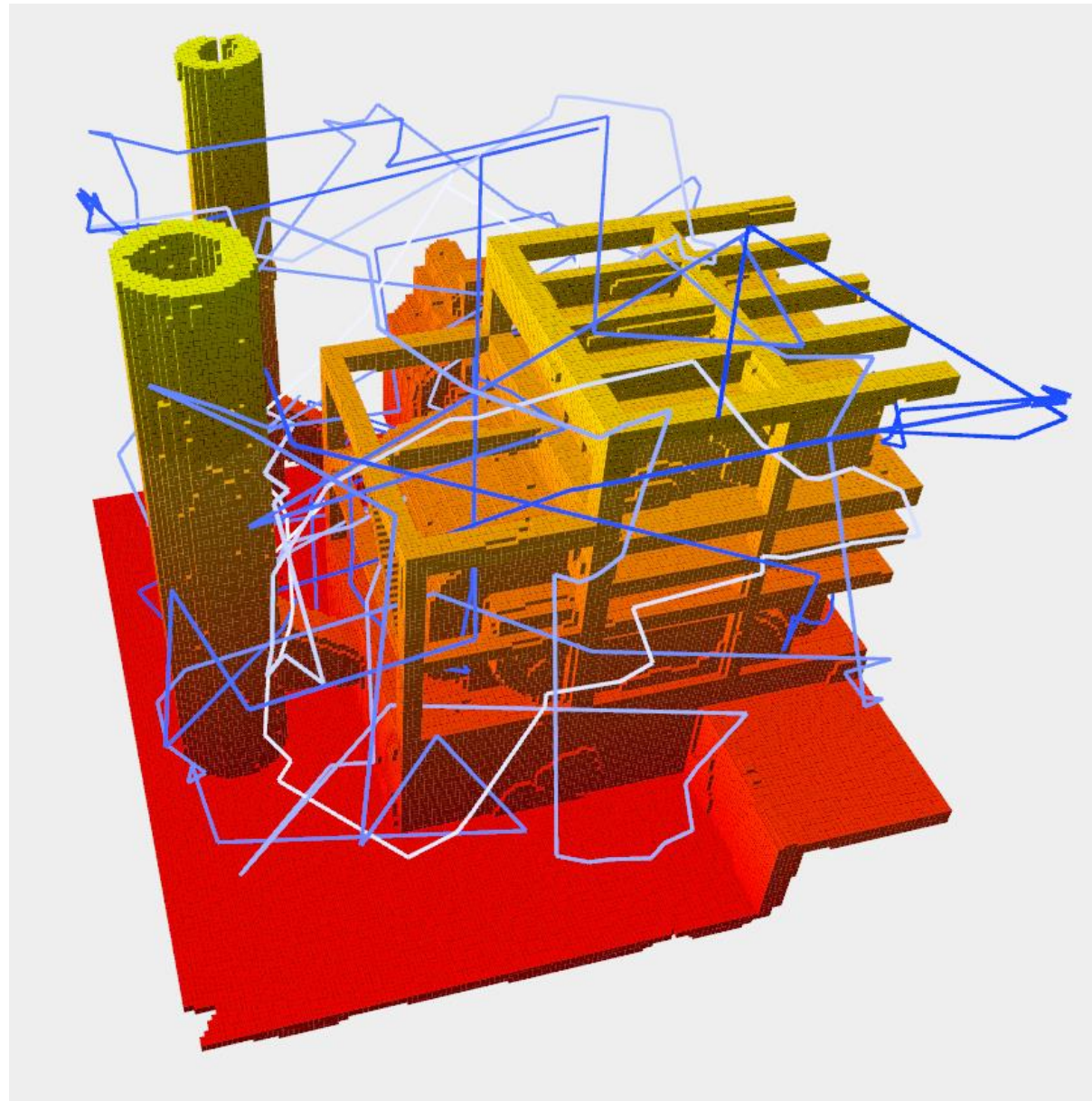
Comparisons



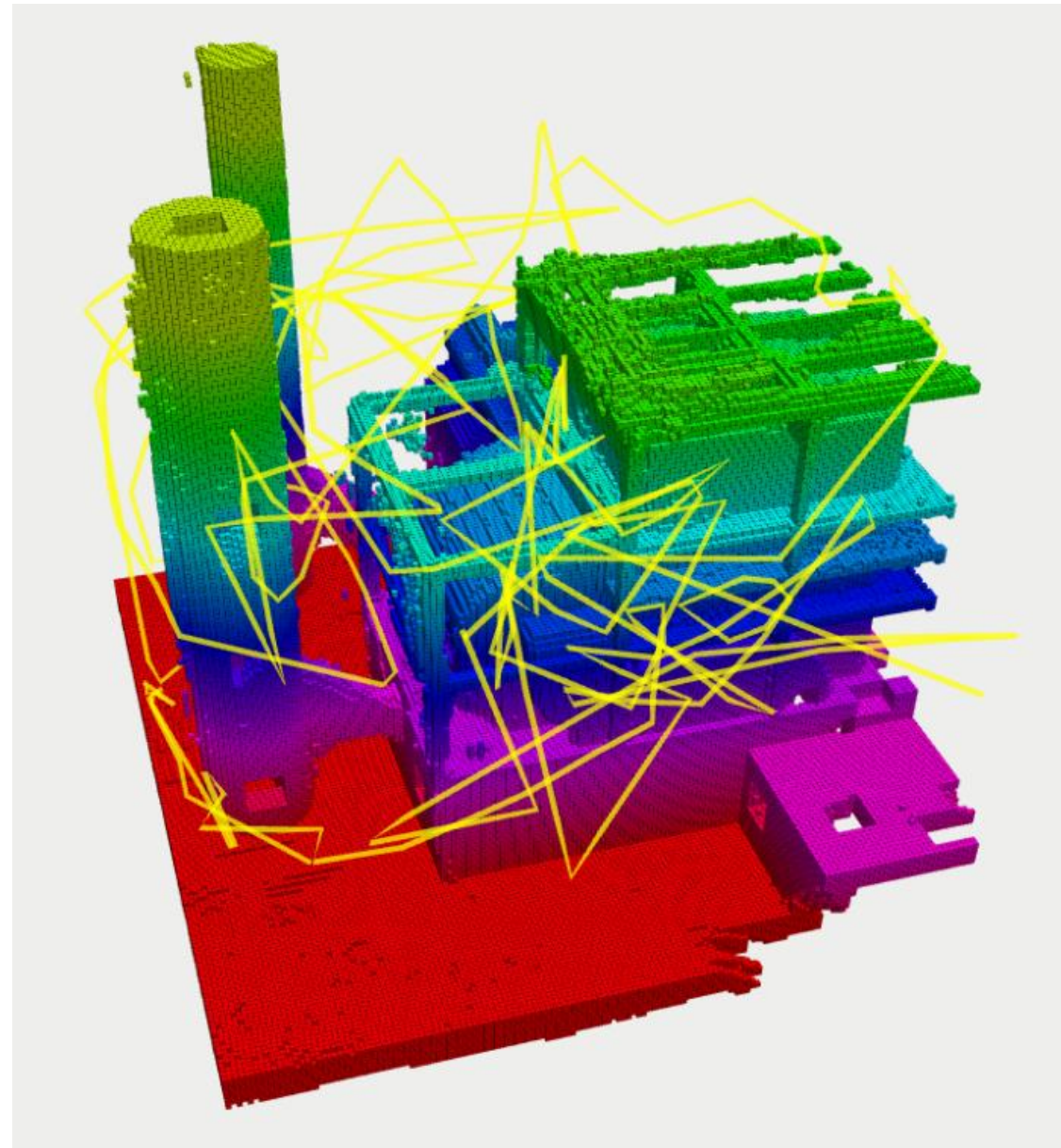
[3] Selin, Magnus, *et al.* "Efficient autonomous exploration planning of large-scale 3-D environments.", *IEEE RAL 2019*.

[22] Schmid, Lukas, *et al.* "An Efficient Sampling-based Method for Online Informative Path Planning in Unknown Environments.", *IEEE RAL 2020*.

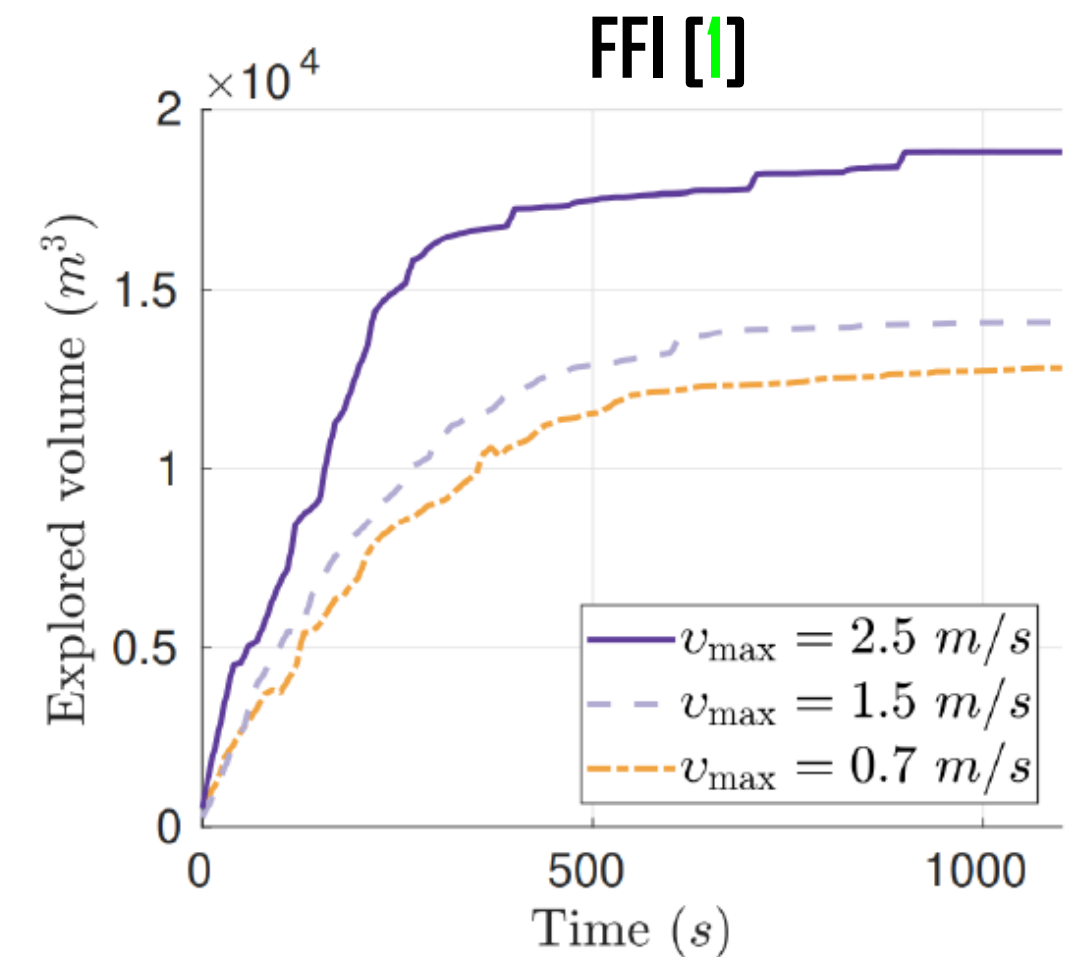
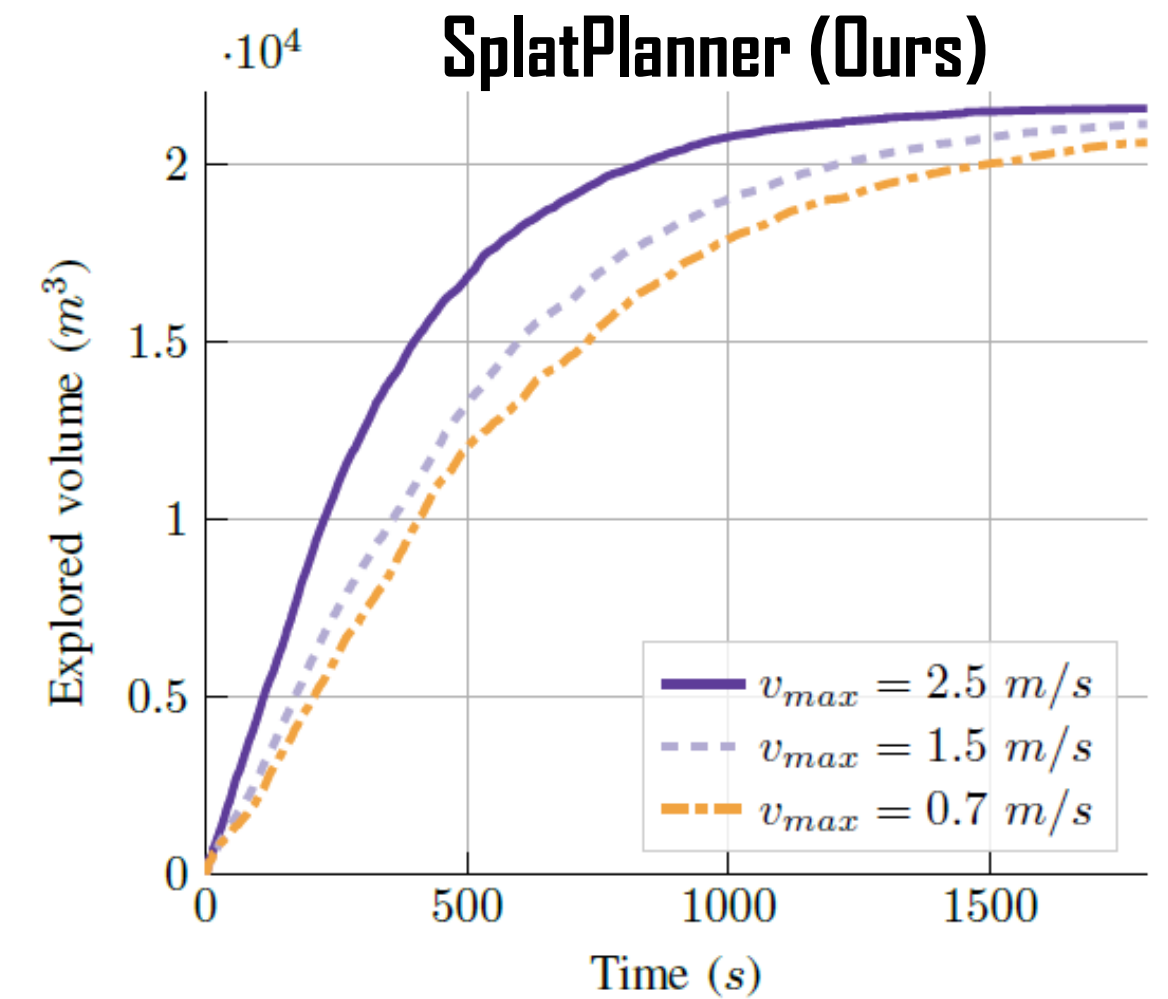
Comparisons



SplatPlanner (Ours)



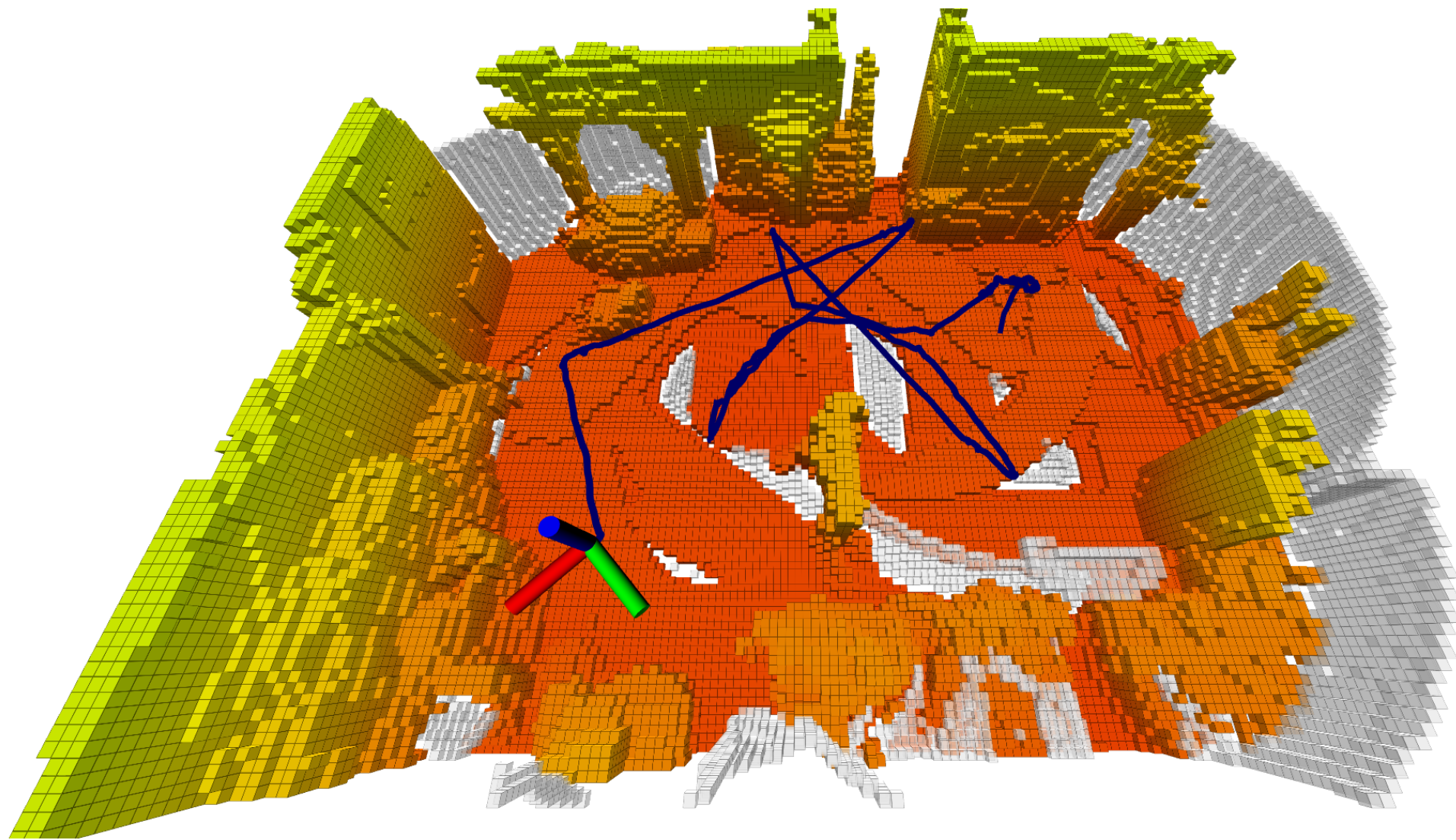
FFI [1]





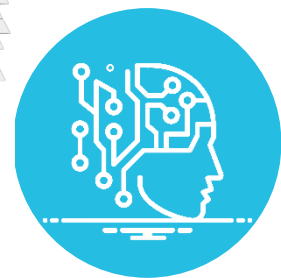
Autonomous flight in our WAREHOUSE

Conclusion



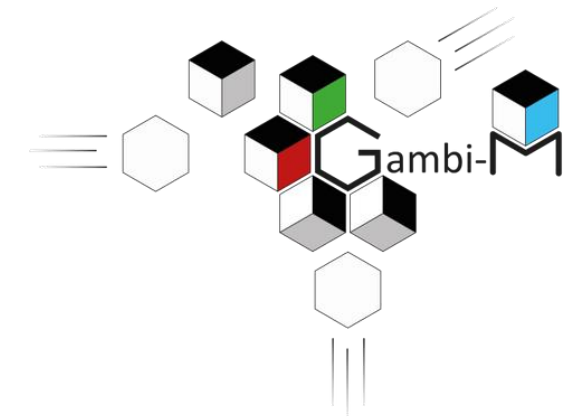
1 Summary

- **Novel frontier selection** relying on our PFF
- ***State-of-the-art*** performance
- Real-flight capabilities



2 Supervised Learning

- Consider higher dimensional features in our PFF
- Extend the framework to semantically aware exploration



Thank you!

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