

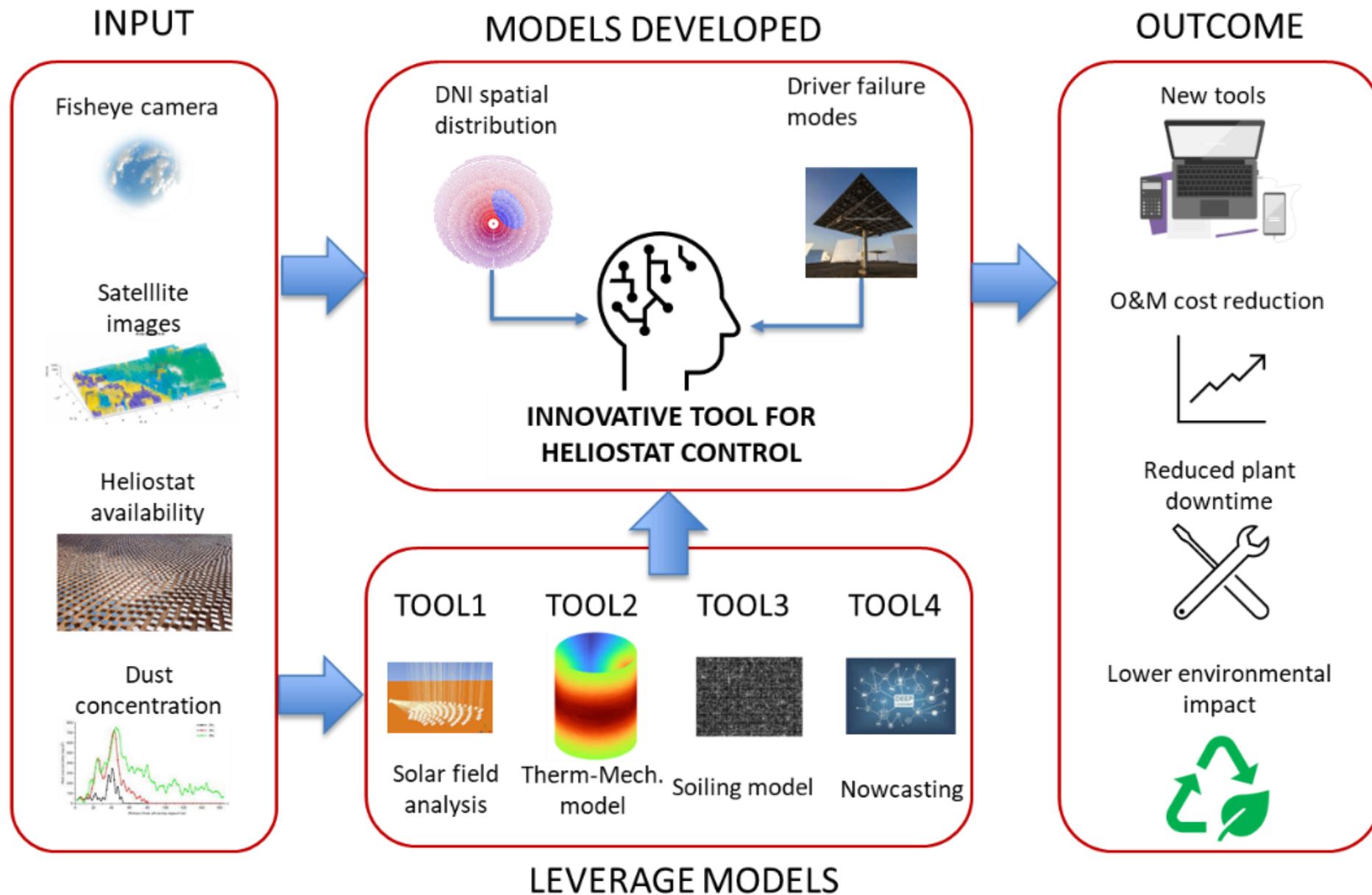
# PROMETHEUS: Predictive and Optimized Control of Heliostats for Future Solar Fields

—  
HelioCon Seminar Series  
October 15, 2025



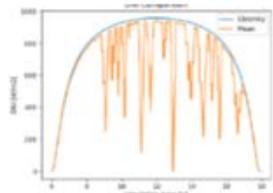
Mike Wagner<sup>1</sup>, Michael Cholette<sup>2</sup>, Giampaolo Manzolini<sup>3</sup>, Emanuele Ogliari<sup>3</sup>

# Predictive and Optimized Control of Heliostats for Future Solar Fields | PROMETHEUS

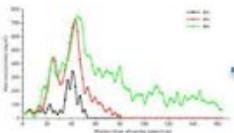
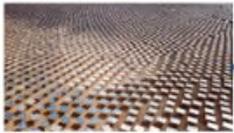




Weather forecast



Heliostat availability



Dust concentration



3

Actual aiming strategy



Clear sky strategy

Weather forecast strategy

1

Fish-eye camera satellite images



2



# Solar Resource Nowcasting



**POLITECNICO**  
MILANO 1863



# Solar Resource Nowcasting Objectives

DNI disturbances can accelerate receiver failure

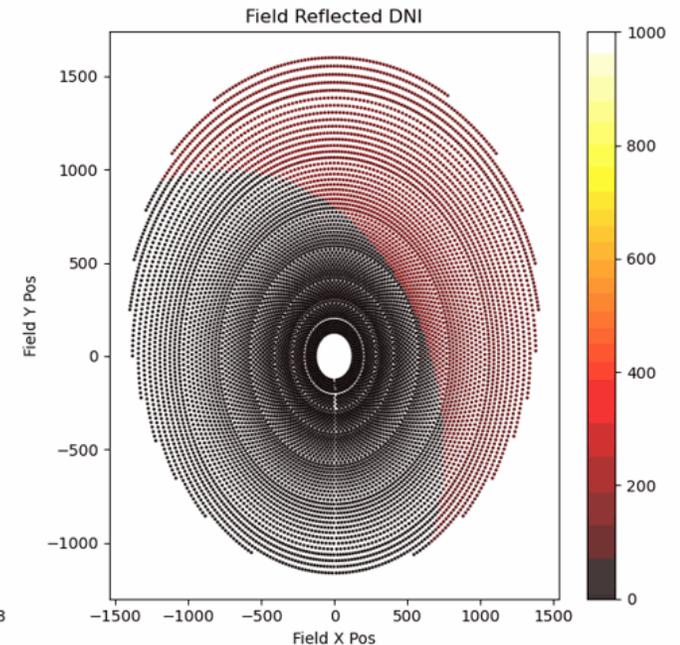
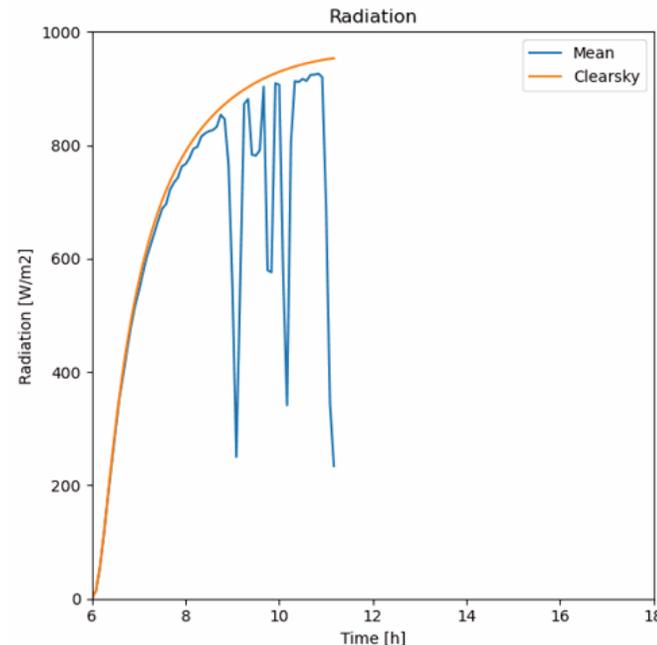
- Clouds drive rapid, large flux-map fluctuations
- Poor control of mass flow and aim points lead to receiver hot spots

Improved spatial DNI forecasts across heliostat-field can inform aiming strategies

- How? Diversification, forecasting, coordination
- Develop & implement two forecasting methods

**Method 1** Centralized all-sky infra-red camera + Satellite Cloud Data

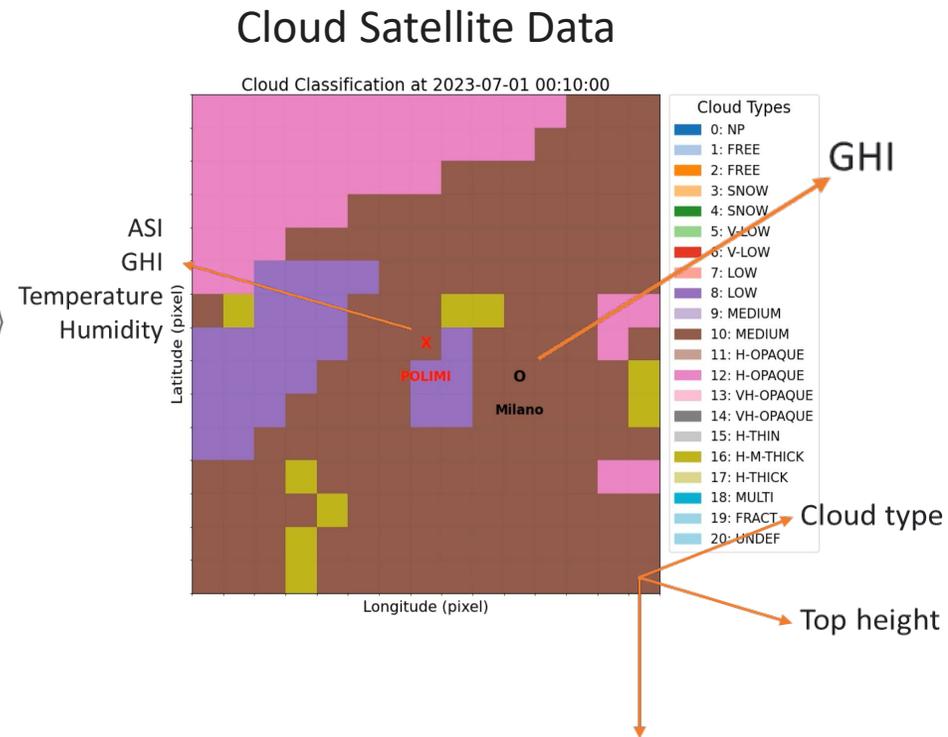
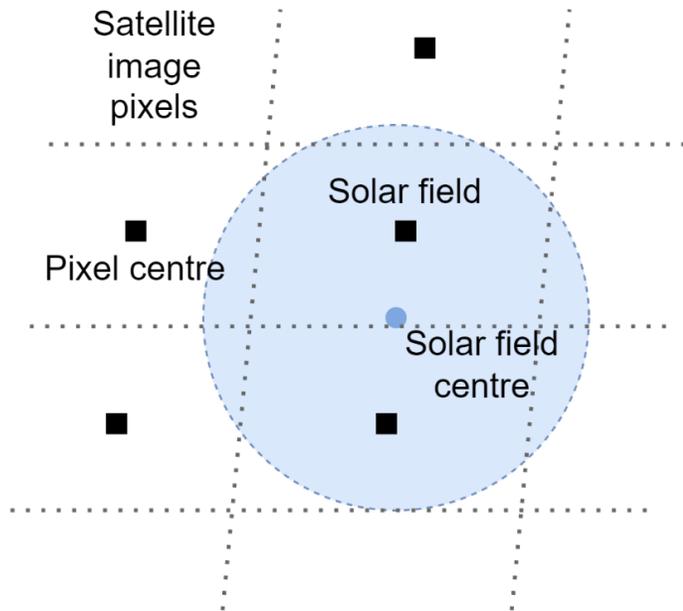
**Method 2** Distributed TinyML + Camera Network





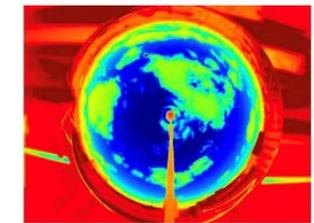
# Centralized All-Sky-Imager and Cloud Satellite Forecaster

Leverage satellite data with all sky imagery to extend from point to spatial predictions



Each pixel includes cloud type and cloud top height.

All-sky-Imager



Neural Network

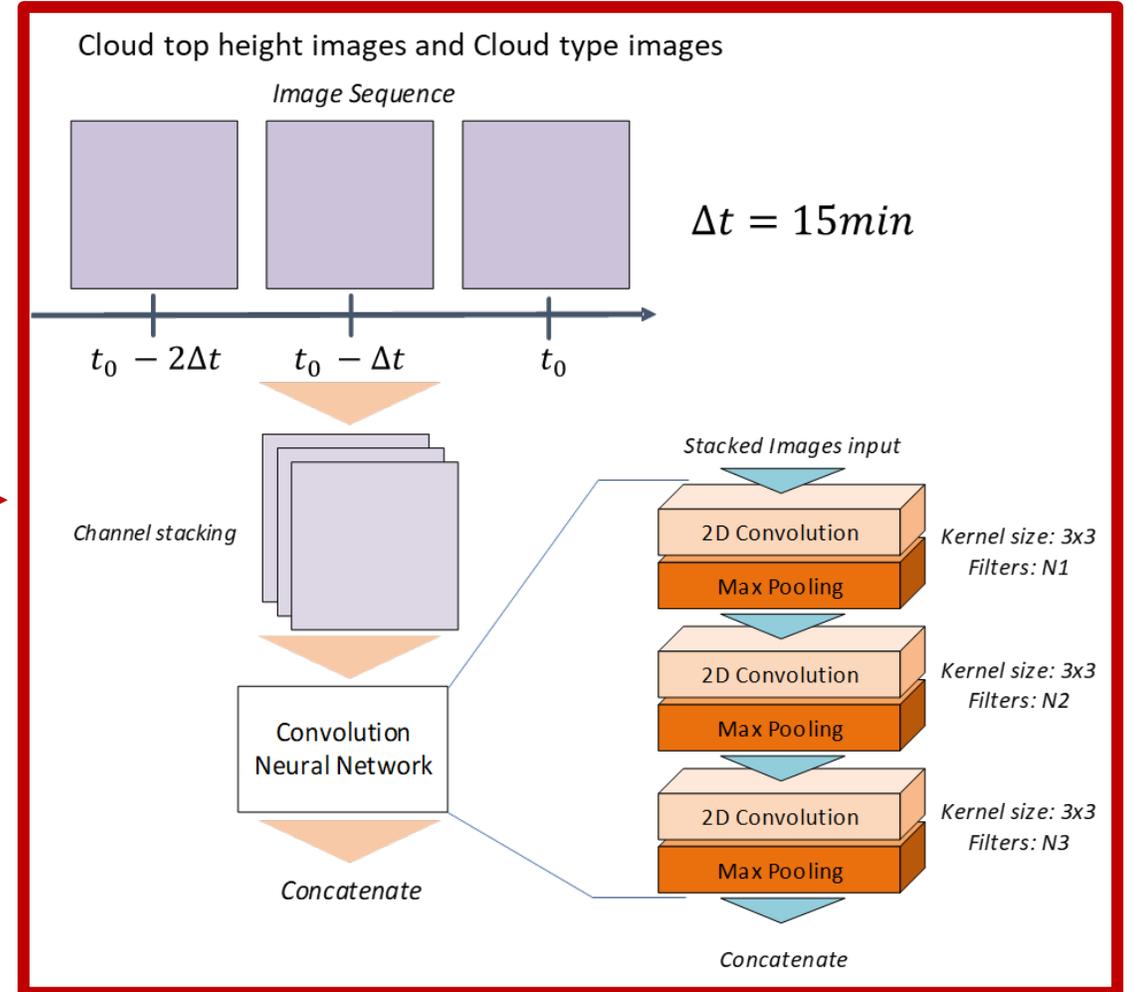
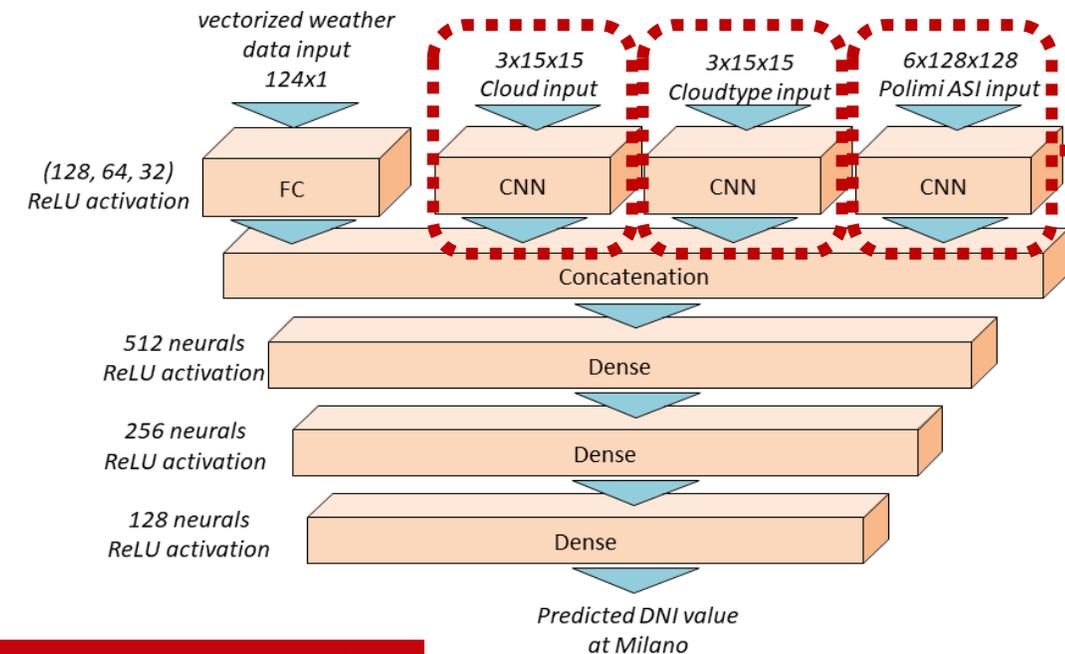
Forecasted DNI in pixel centres



# CNNs for Solar Radiation Nowcasting

## Input Data:

- Satellite Images (Cloud top height and cloud type)
- All-Sky-Camera Infrared Images
- Weather Data ( $DNI_{Target}$  &  $ASI_r$ , Temperature, Humidity)

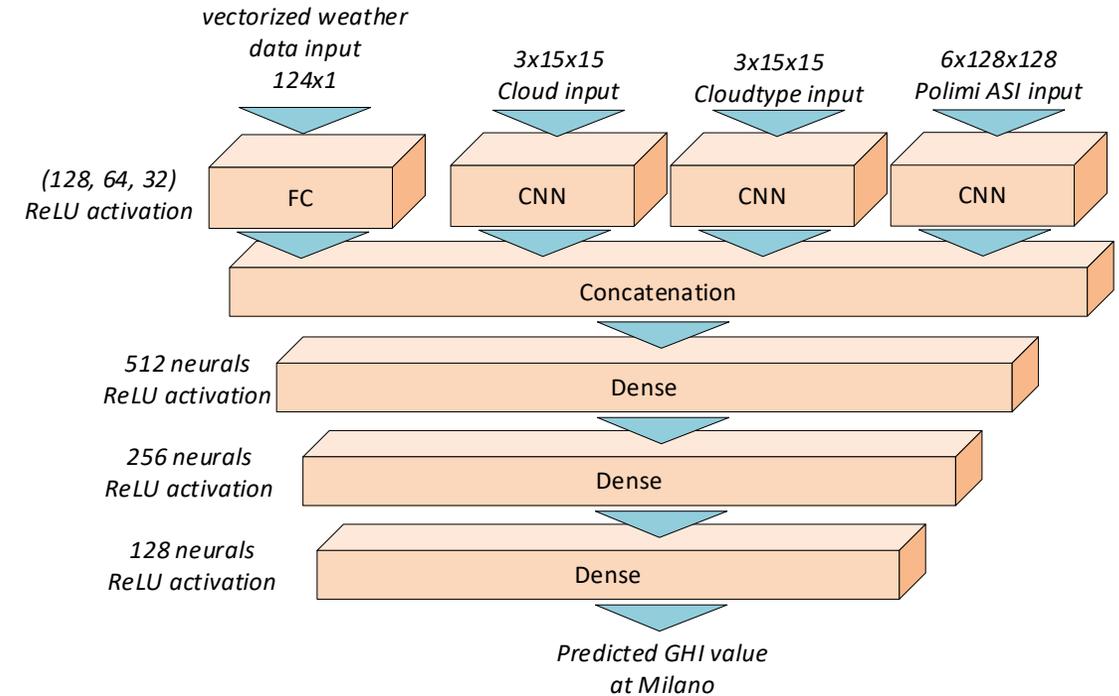


# Forecasting Example

At **10:40:00**, the goal is to **forecast GHI** at Milano station at **10:55:00** (15 minutes ahead)

The following input data are used for prediction:

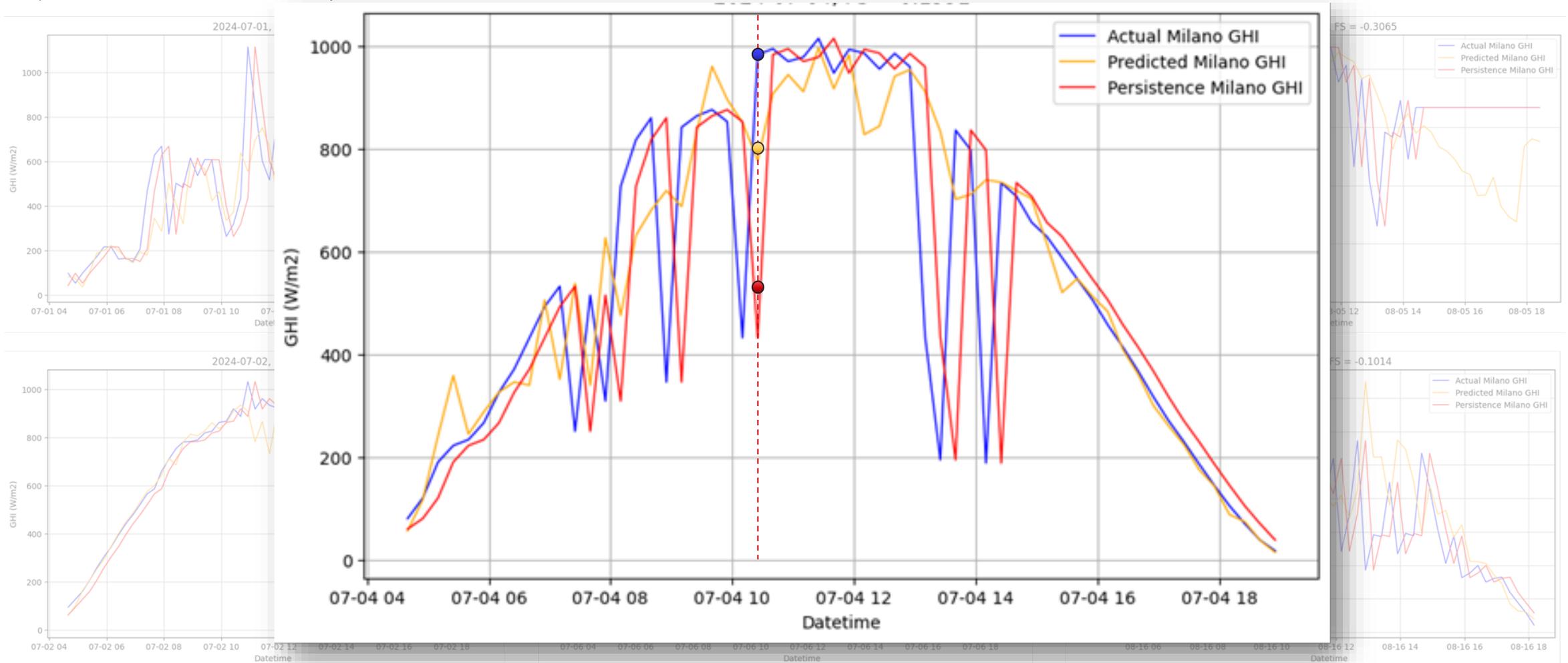
- **Satellite Images:**
  - **Cloud Top Height and Cloud Type**
  - Taken at **10:10:00, 10:25:00, and 10:40:00**
  - **Temporal sampling:** every 15 minutes ( $\Delta t = 15$  mins)
  - Total: **3 images**
  - Spatial resolution: **15×15 pixels**
- **All-Sky Images (ASI):**
  - Originally recorded **every 1 minute**
  - For input, select frames every 2 minutes between **10:30:00 and 10:40:00**
  - Total: **6 images**
  - Spatial resolution: **128×128 pixels**
- **Weather Data**
  - 4 meteorological features (Polimi\_GHI, Polimi\_temperature, Polimi\_humidity, Milano\_GHI)
  - Recorded every 1 minute from **10:10:00 to 10:40:00**
  - Total: **31 timestamps × 4 features = 124 values**



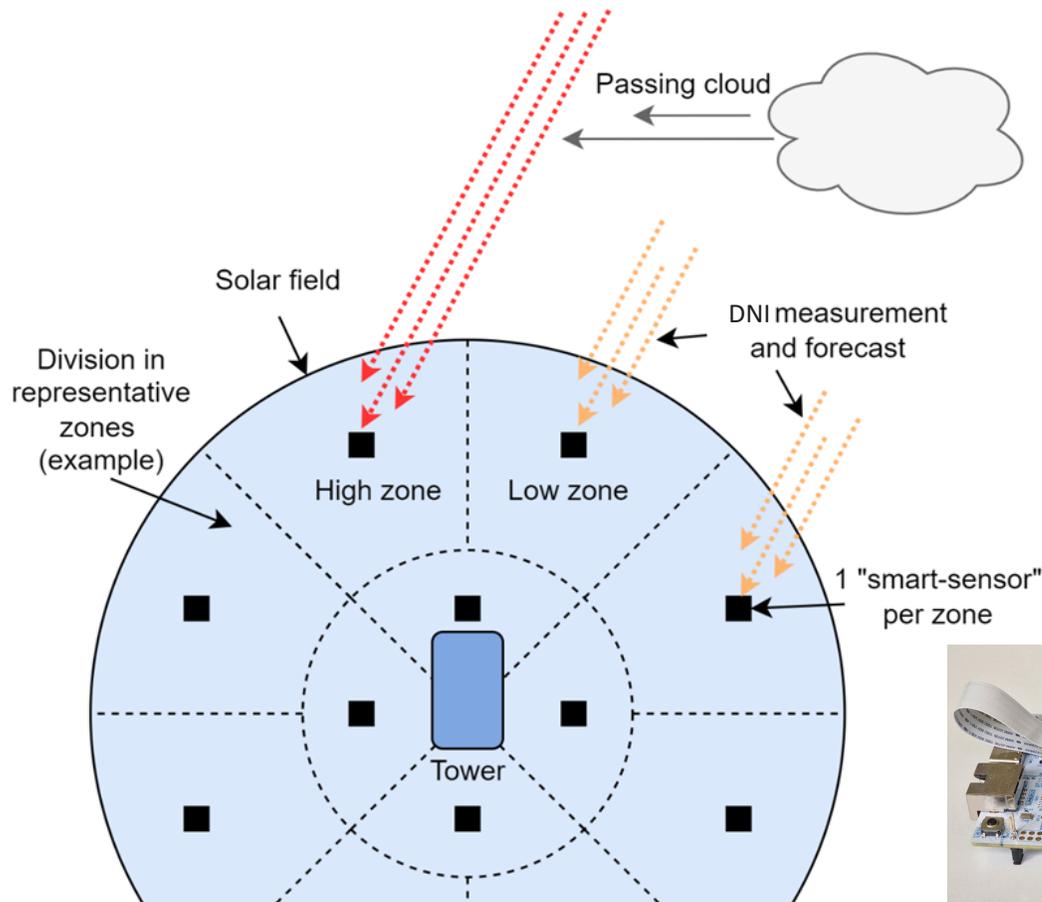


## Preliminary Results: Target-GHI Milano with PoliMi GHI

(Distance = 8.38 km)



# Distributed Forecaster TinyML + Camera Network



- TinyML + Camera distributed evenly in the field
- Forecast DNI for a zone decides the mirrors' position
- Price per device around 100 € (all sky camera around 60 k€)

TinyML



Neural  
Network

Forecasted  
DNI point



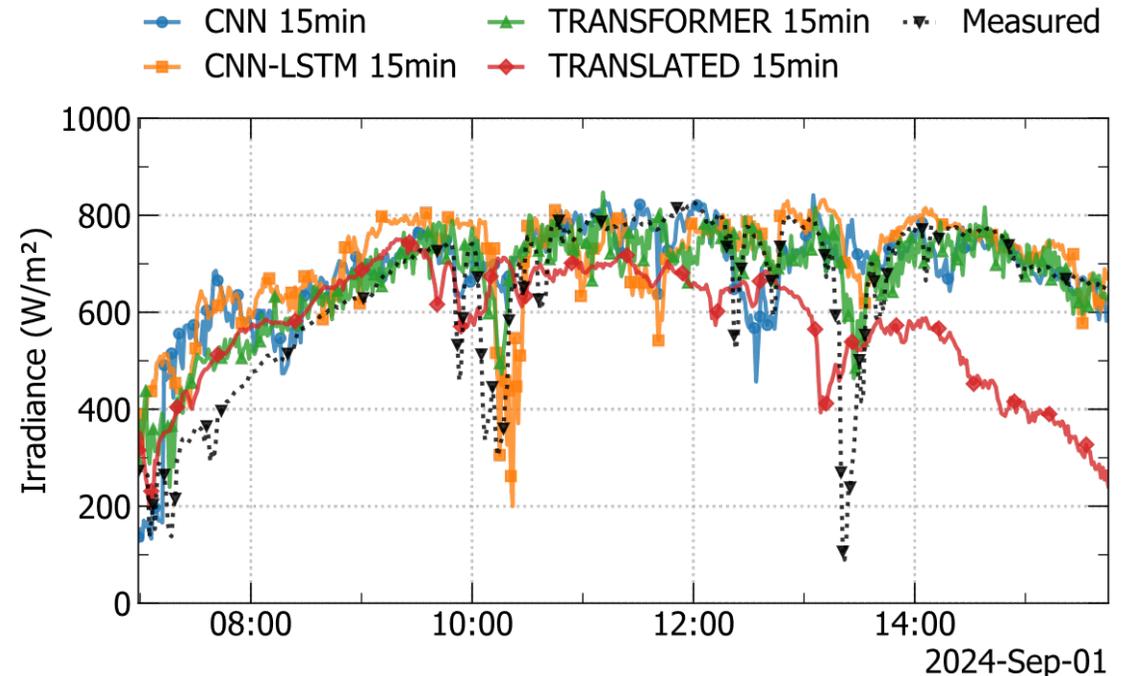
# Solar Resource Forecasting Progress and Future Work

- Tested spatial-GHI ASI+Cloud forecaster
- Benchmarked point-DNI neural network forecasters

Next steps are to:

- Implement spatial-DNI forecasts with satellite cloud methodology
- Develop TinyML for field testing and comparison with Method 1

## DNI Neural Network Forecast Comparison



DNI Horizon	MAE [W/m <sup>2</sup> ]	MBE [W/m <sup>2</sup> ]	FS [%]
Transformer-15m	92	-5	22
Transformer-10m	68	0	47
Transformer-5m	52	-9	36

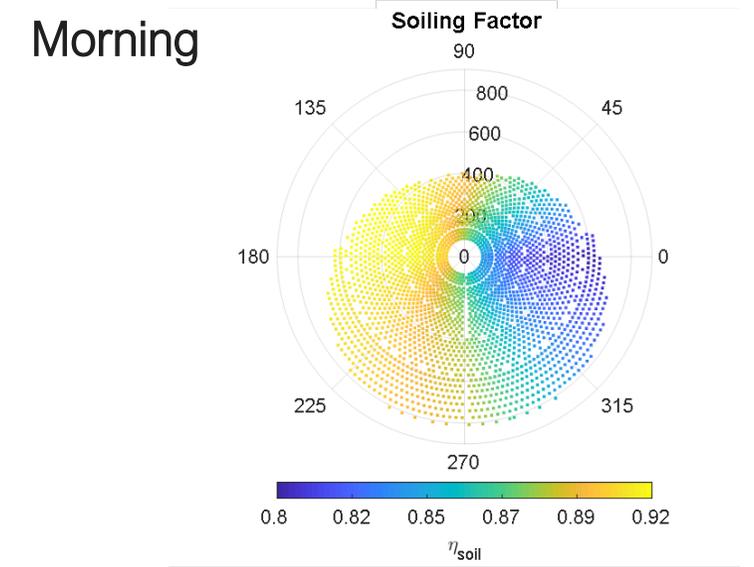
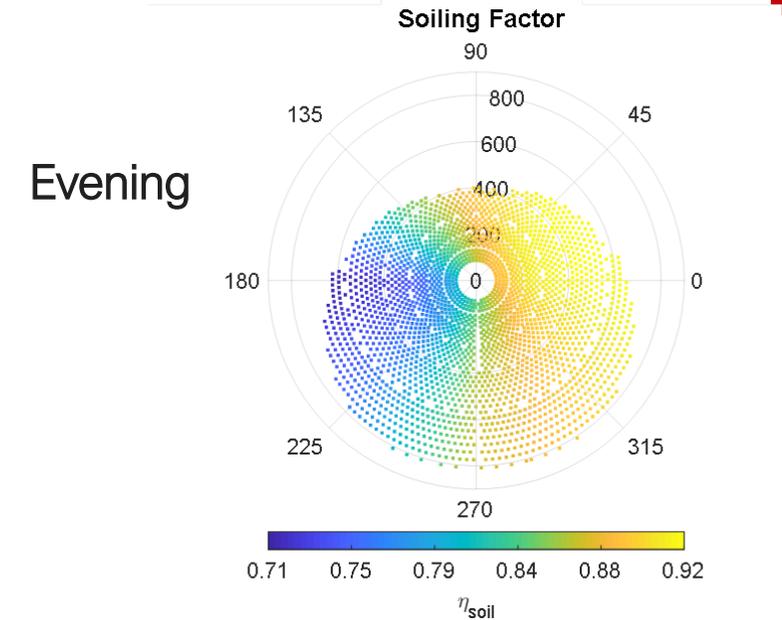


# Heliostat Field State Monitoring

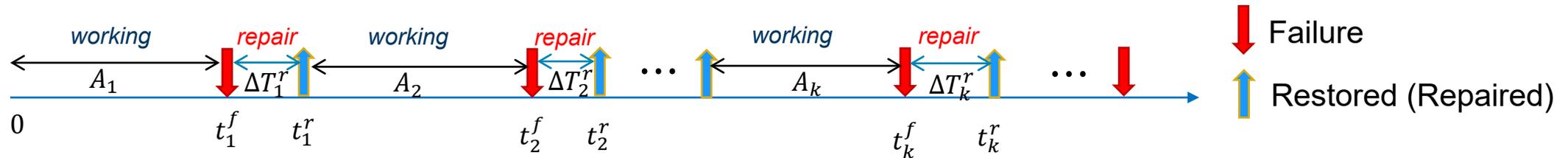


# Spatial soiling effects can be captured in aiming strategies

- Both soiling and heliostat unavailability affect the flux profile
- Soiling accumulation is uneven, and impact varies with incidence angle
  - This leads to significant hourly changes in individual heliostat reflectance
- Heliostats unavailability may drive the need for adaptation of the aiming strategy
- This task concerned with:
  - Integrating soiling models with aiming optimization tools
  - Developing reliability models and simulating the heliostat statuses
  - Developing strategies to respond to the current soiling status



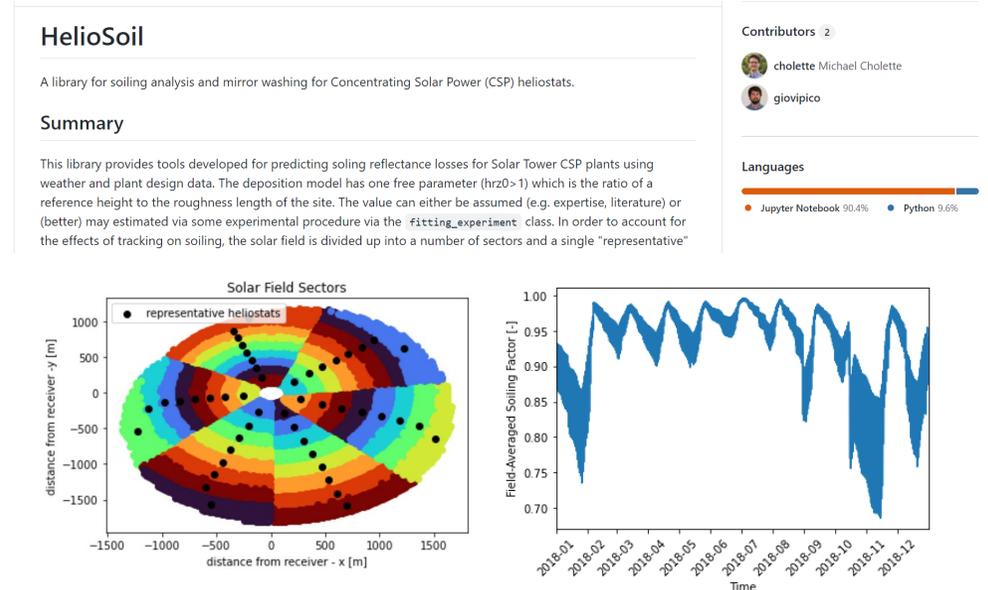
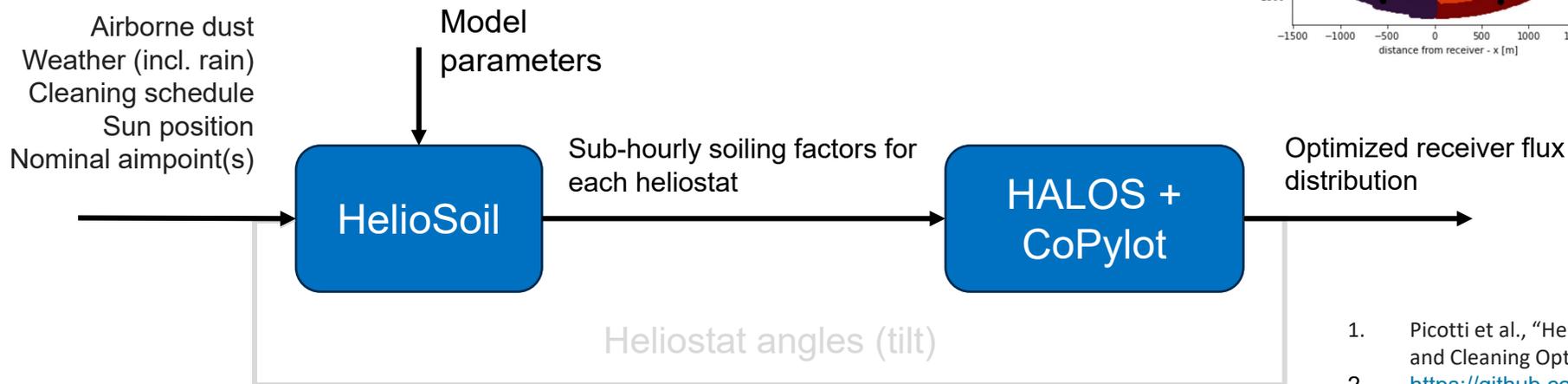
# Availability model & simulation



- An individual heliostat transitions between working and failed states via failure and repair processes
- Failures of heliostats are assumed independent and have fixed rates  $\lambda_i^f$  ( $i = 1, 2 \dots N_{heliostat}$ )  $\rightarrow$  Working time (lifetime) of heliostat  $i$  until failure:  $A_{i,k} \sim \text{Exp}(\lambda_i^f) \quad \forall k$
- Repair times are the same for all heliostats, and also have a fixed rate  $\lambda^r \rightarrow \Delta T_k^r \sim \text{Exp}(\lambda^r) \quad \forall k$
- Enables availability status simulation of thousands of heliostats in seconds

# Incorporating soiling into HALOS and SolarPILOT

- Main optimization framework is expected to be provided by HALOS, which uses flux maps provided by SolarPILOT.
- Heliosoil<sup>1,2</sup> provides soiling factors for each heliostat, which are then supplied to SolarPILOT via the CoPylot API<sup>3</sup>

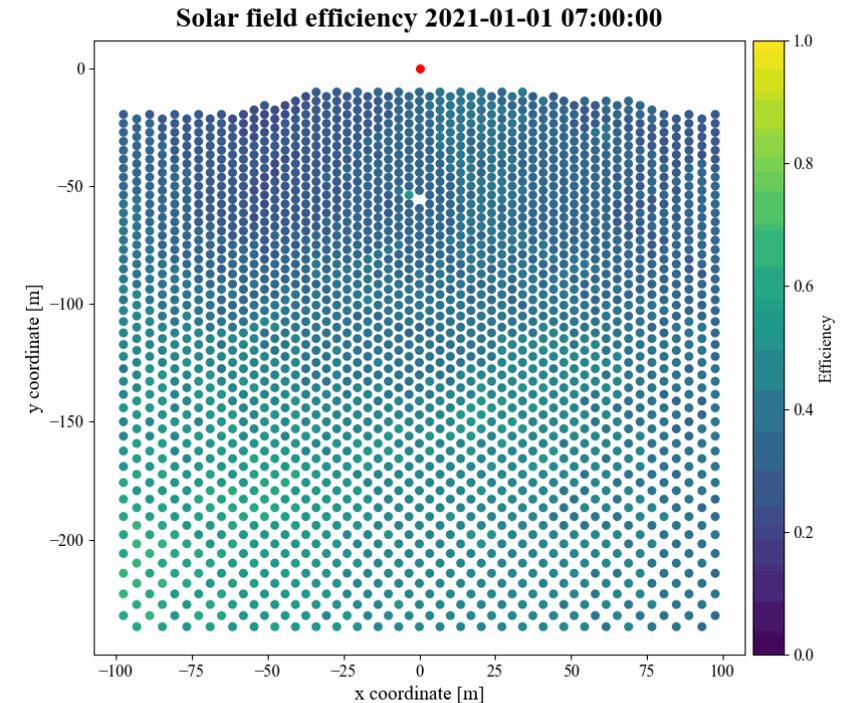


1. Picotti et al., "HelioSoil: A Python Library for Heliostat Soiling Analysis and Cleaning Optimization," SolarPACES 2022
2. <https://github.com/cholette/HelioSoil>
3. Hamilton "Demonstrating solarpilot's Python Application Programmable Interface Through Heliostat Optimal Aimpoint Strategy Use Case," *J. Sol. Energy Eng* 2022

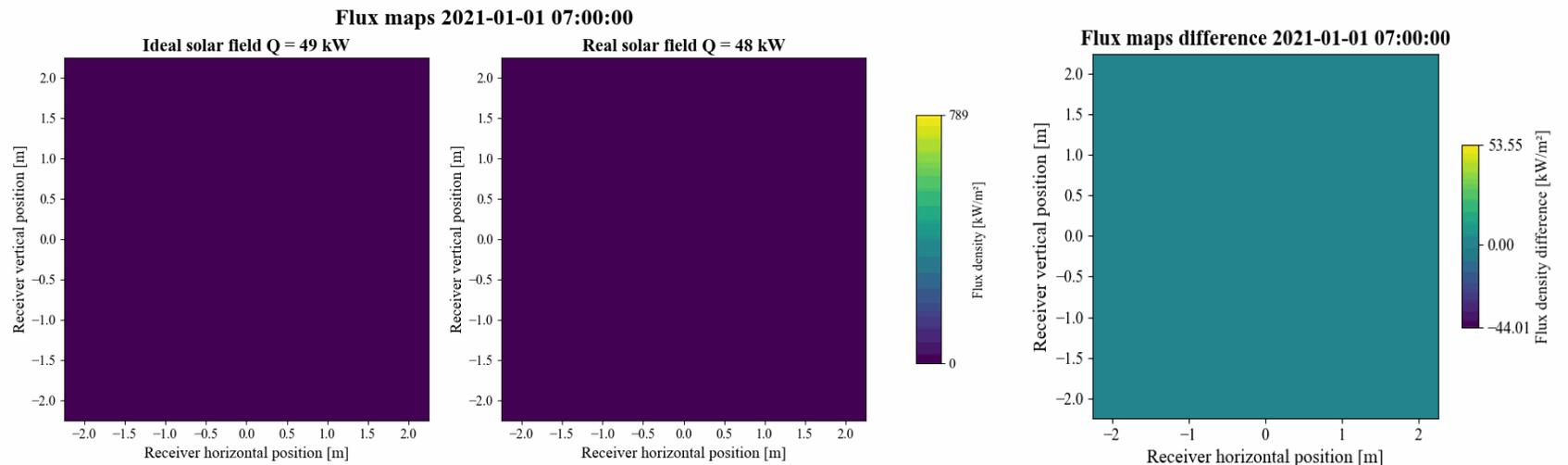


# Soiling and availability simulation

- Proof of concept simulation implemented in Python
- A soiling trajectory is applied to the field, cleaning is included
- Efficiency values are a combination of the nominal optical efficiency, the soiling factor, and the availability
- Unavailable heliostats have zero efficiency for their downtime
- Availability and soiling simulations take seconds for this field



*Flux map on billboard receiver (4.5m x 4.5m)*





# Flux management

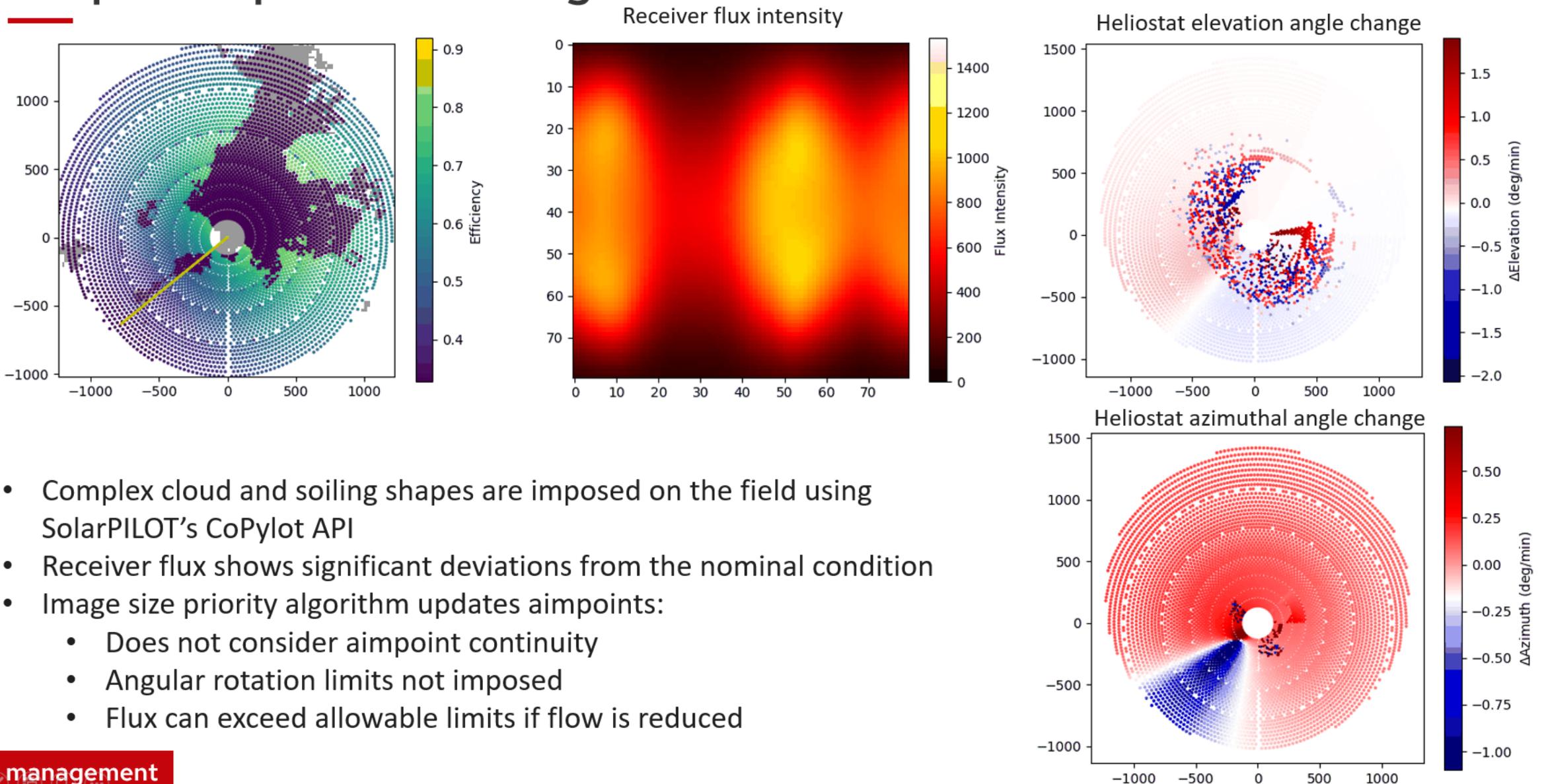
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## Contributors:

Jacob Wenner (PhD student)

Dean Izzo (BS student)

# Dynamic conditions require improved aimpoint optimization algorithms



- Complex cloud and soiling shapes are imposed on the field using SolarPILOT's CoPilot API
- Receiver flux shows significant deviations from the nominal condition
- Image size priority algorithm updates aimpoints:
  - Does not consider aimpoint continuity
  - Angular rotation limits not imposed
  - Flux can exceed allowable limits if flow is reduced

# Thermal Loading On Receiver Tubes

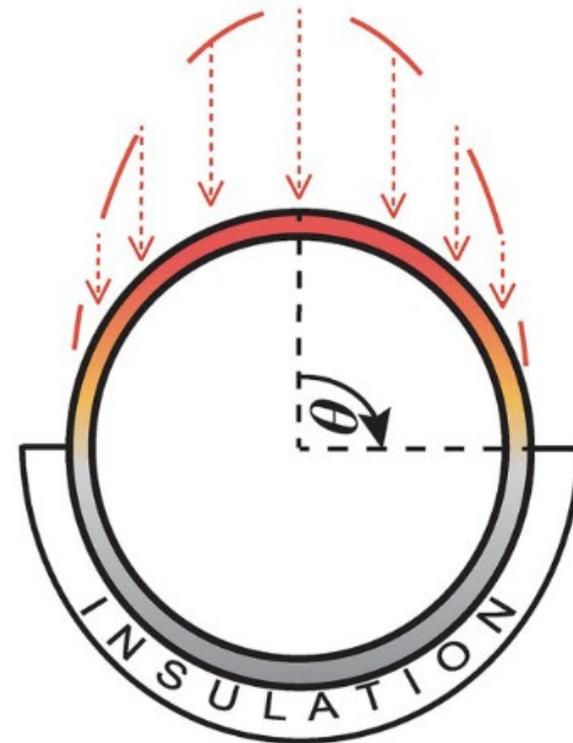
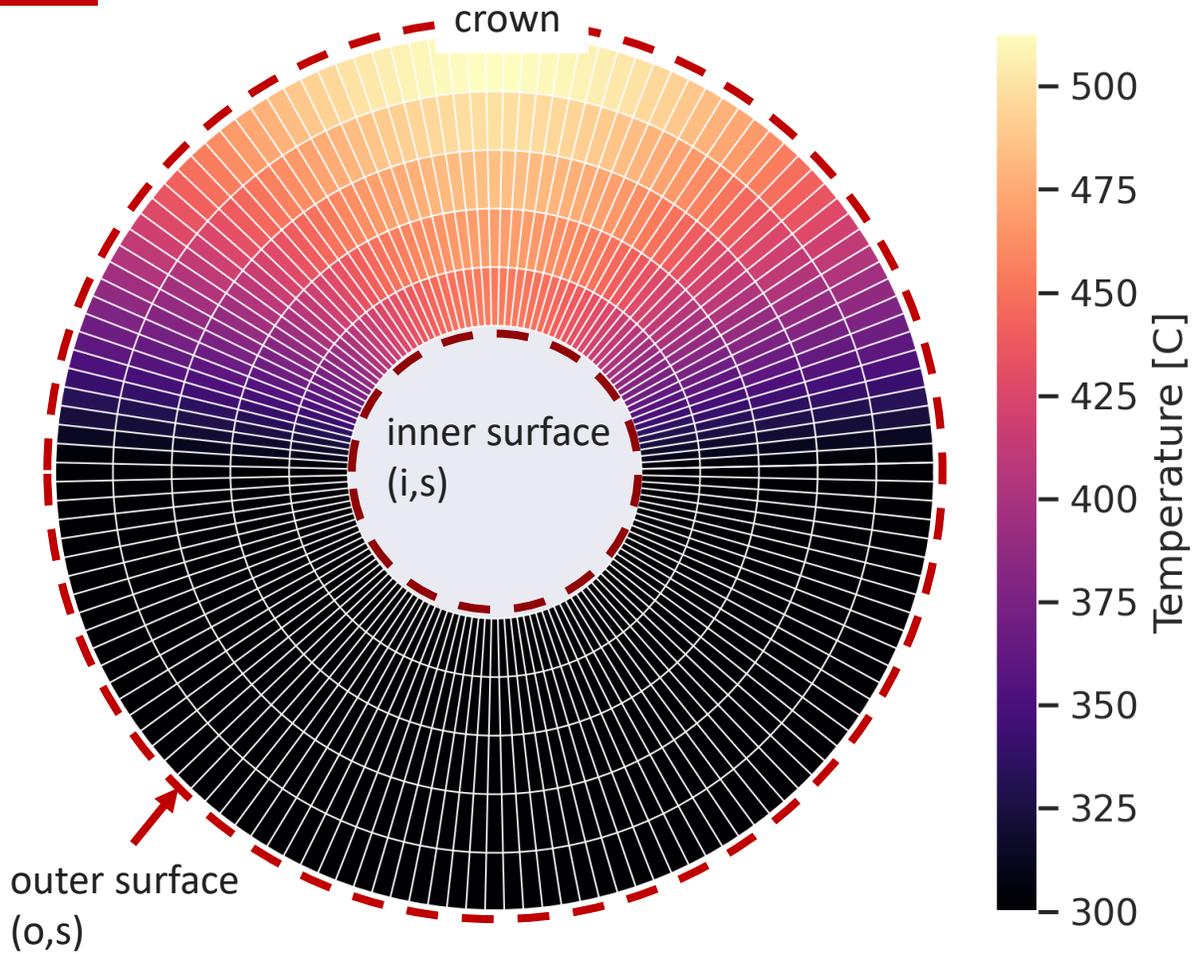
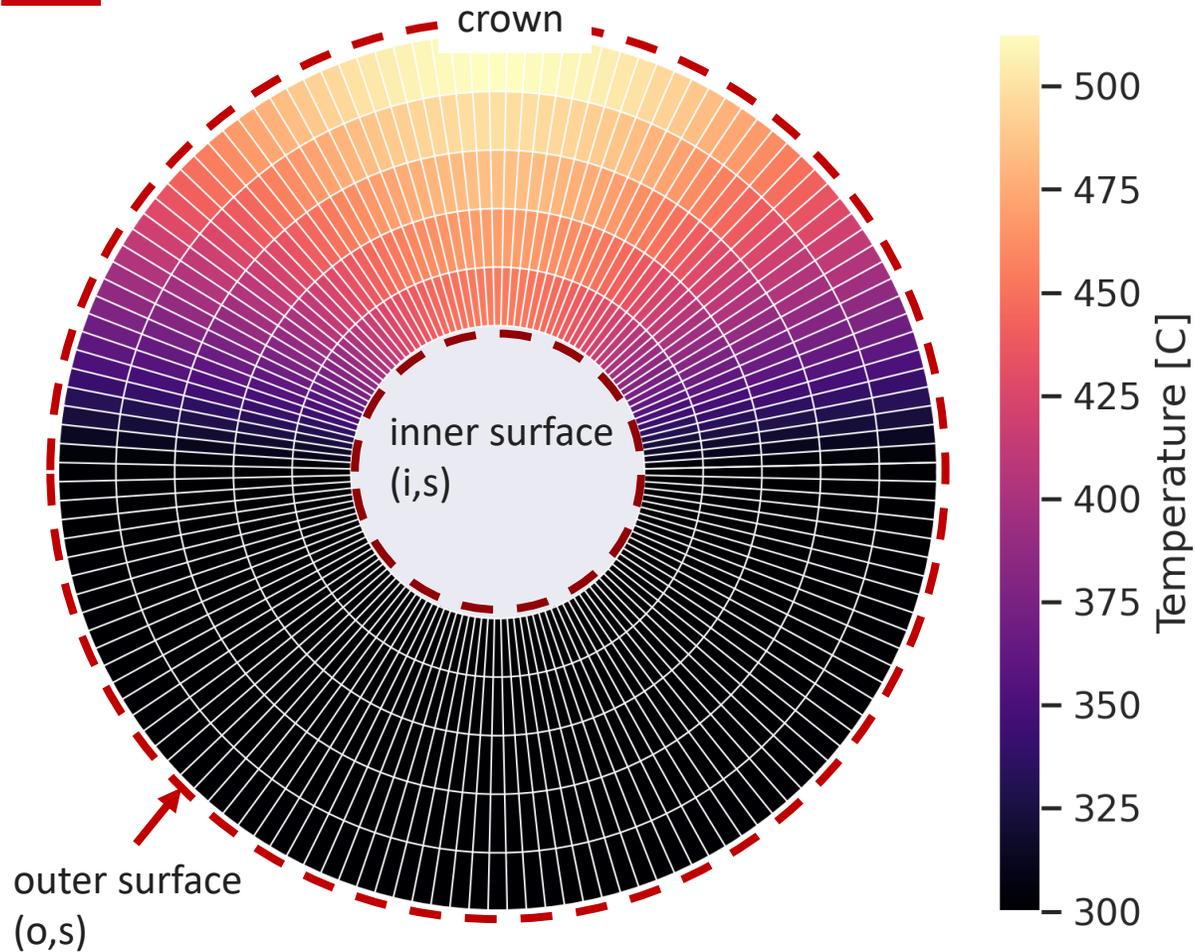


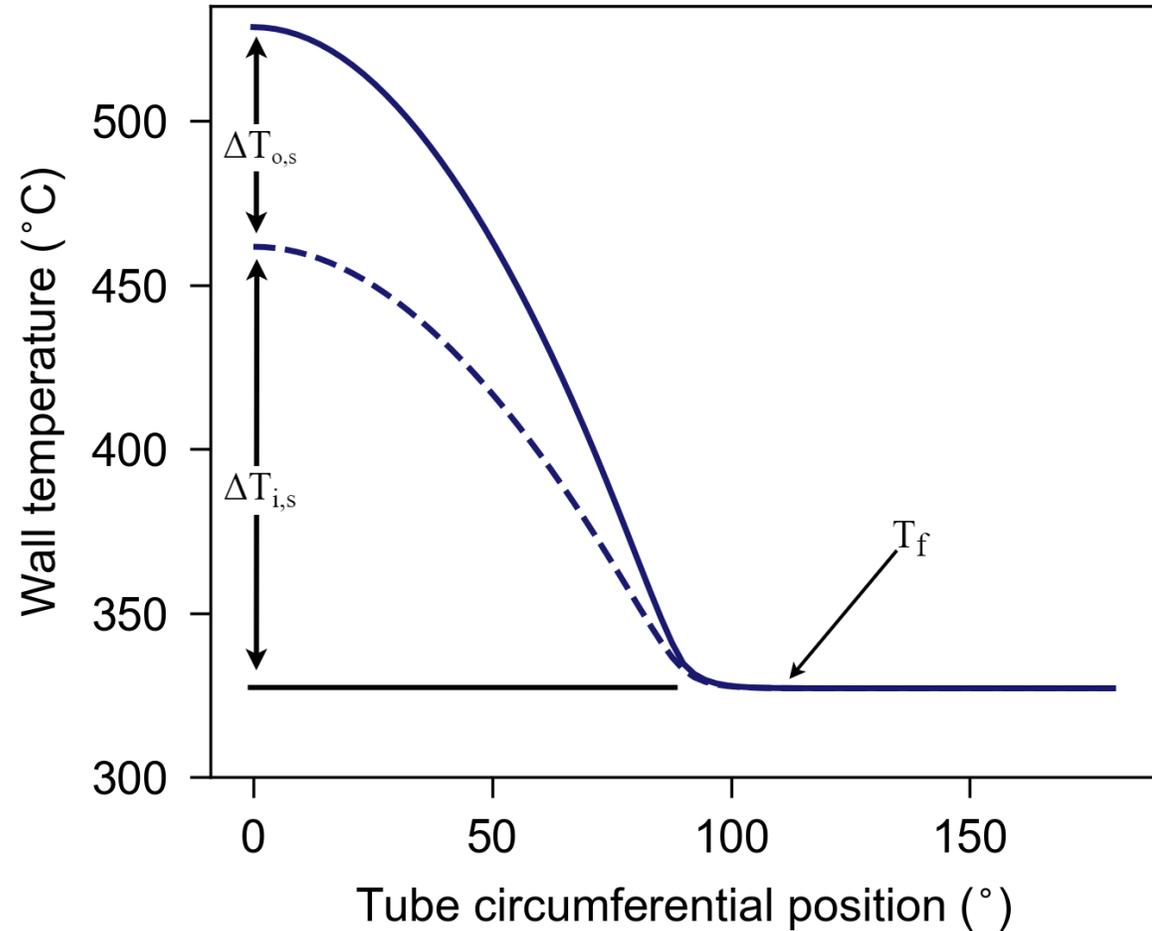
Illustration showing tube flux as a function of position from Conroy et al. (2020) [1]

Cross section for a tube subject to surface boundary conditions similar to right – 300 fluid temperature (C) and 220 total temperature difference (C)

# Thermal Loading On Receiver Tubes



Cross section for a tube subject to surface boundary conditions similar to right – 300 fluid temperature (C) and 220 total temperature difference (C)



Outer and inner surface temperature of a representative tube in a commercial CSP plant. Figure made using thermal model from [3]



# Creep and Fatigue Damage

## Fatigue damage

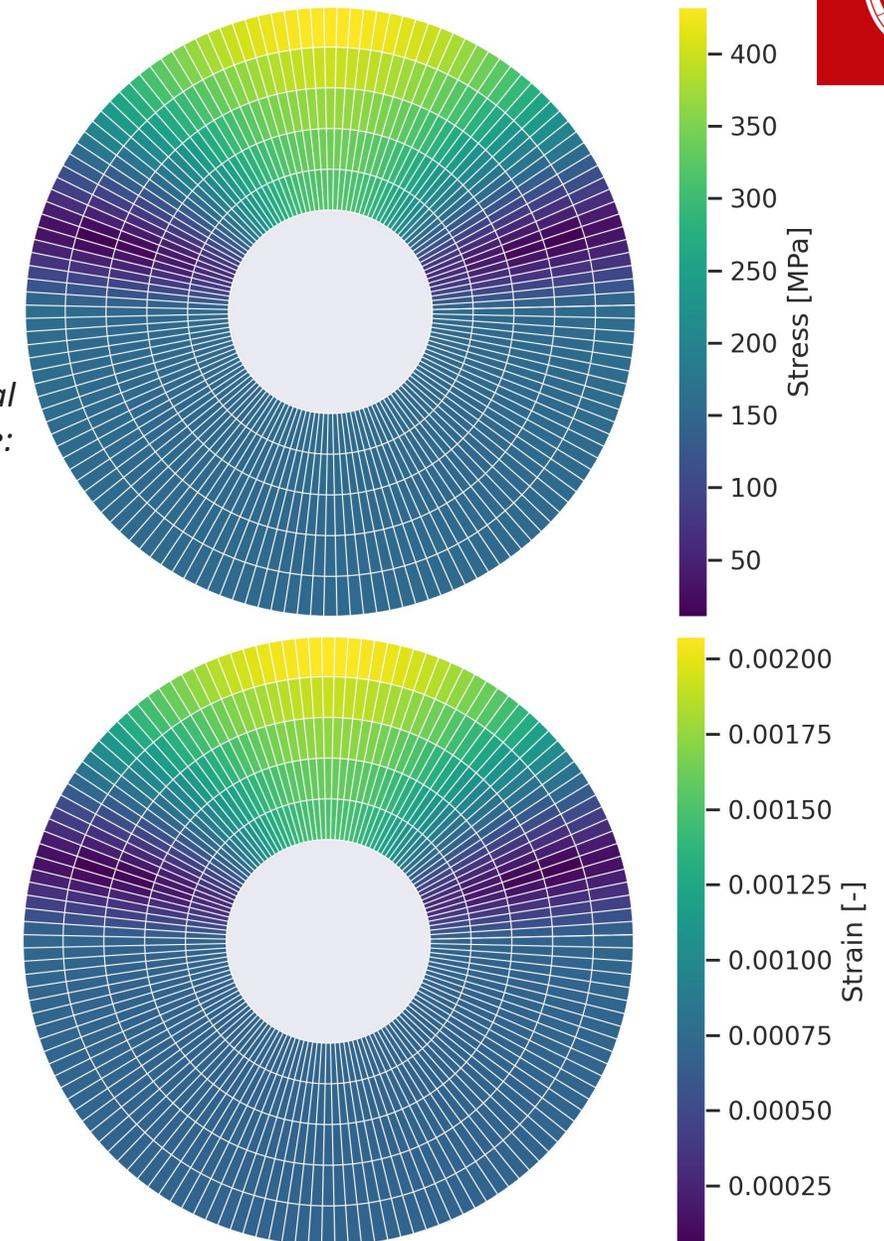
- results from cyclic strain/stress
- cycle dependent
- temperature dependent

## Creep damage

- irreversible relaxation that occurs at elevated metal temperature
- time dependent
- highly temperature dependent

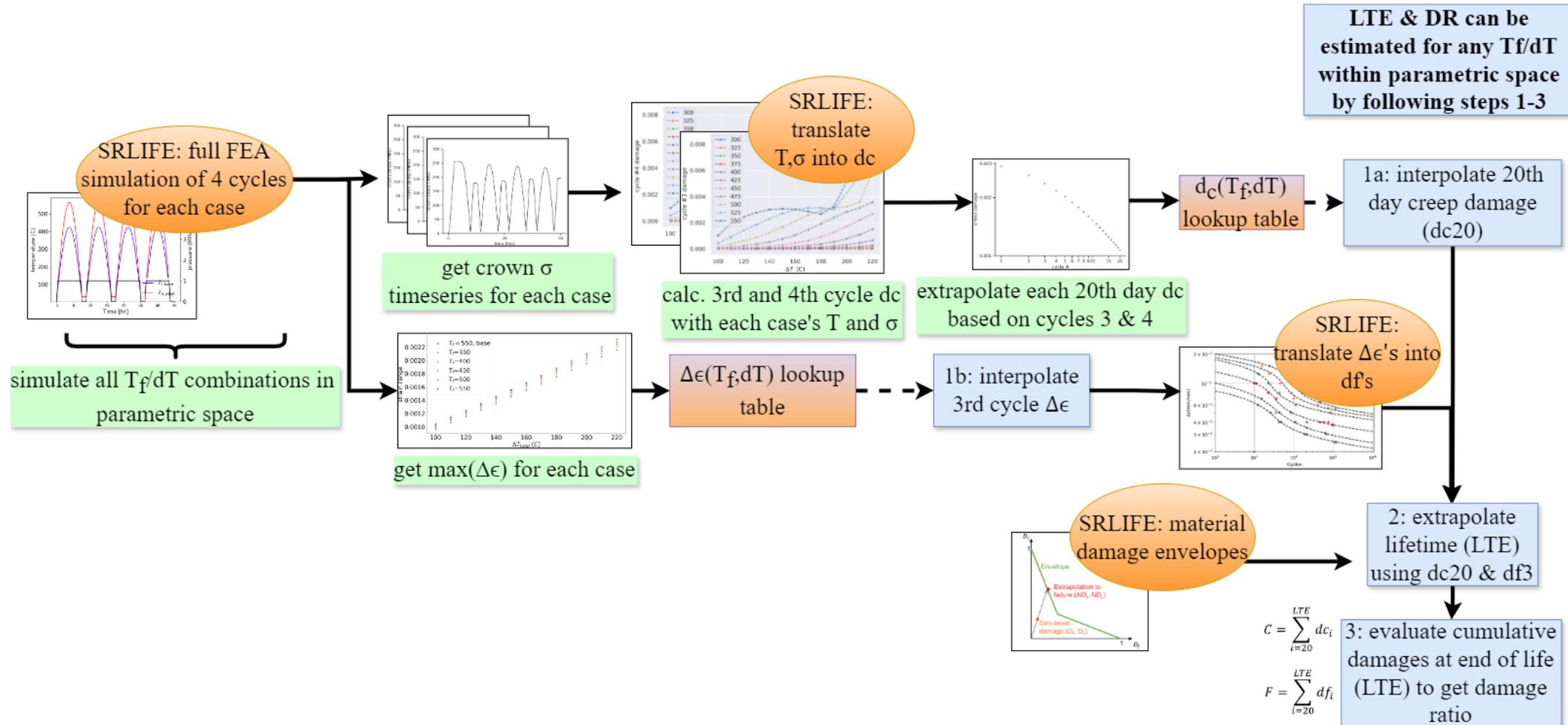
$$d_c = \int \frac{1}{T_d(\sigma, T)} dt$$

*FEA elastic simulation via [4] of a tube at 300 [C] fluid temperature and 220 [C] total temperature difference. Note: thickness exaggerated.*



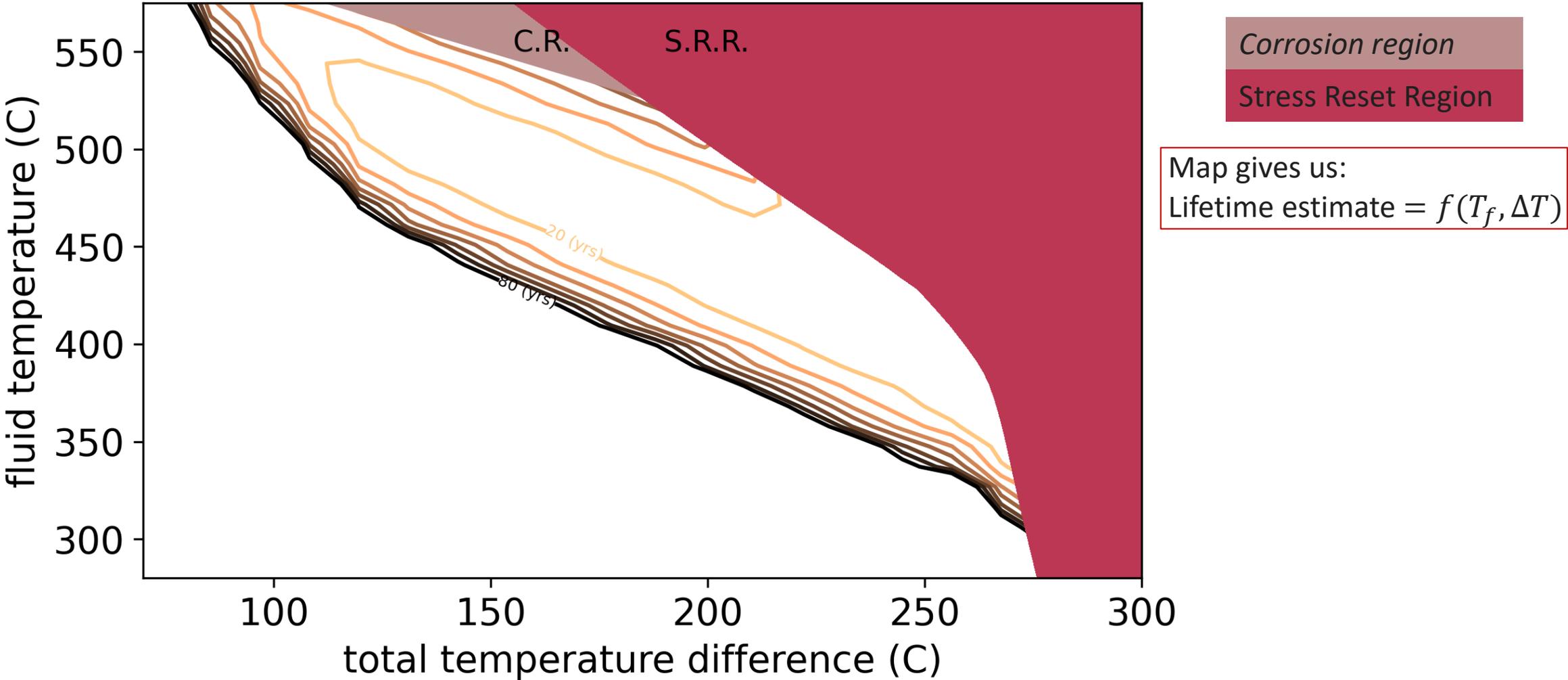


# Lifetime modeling methodology



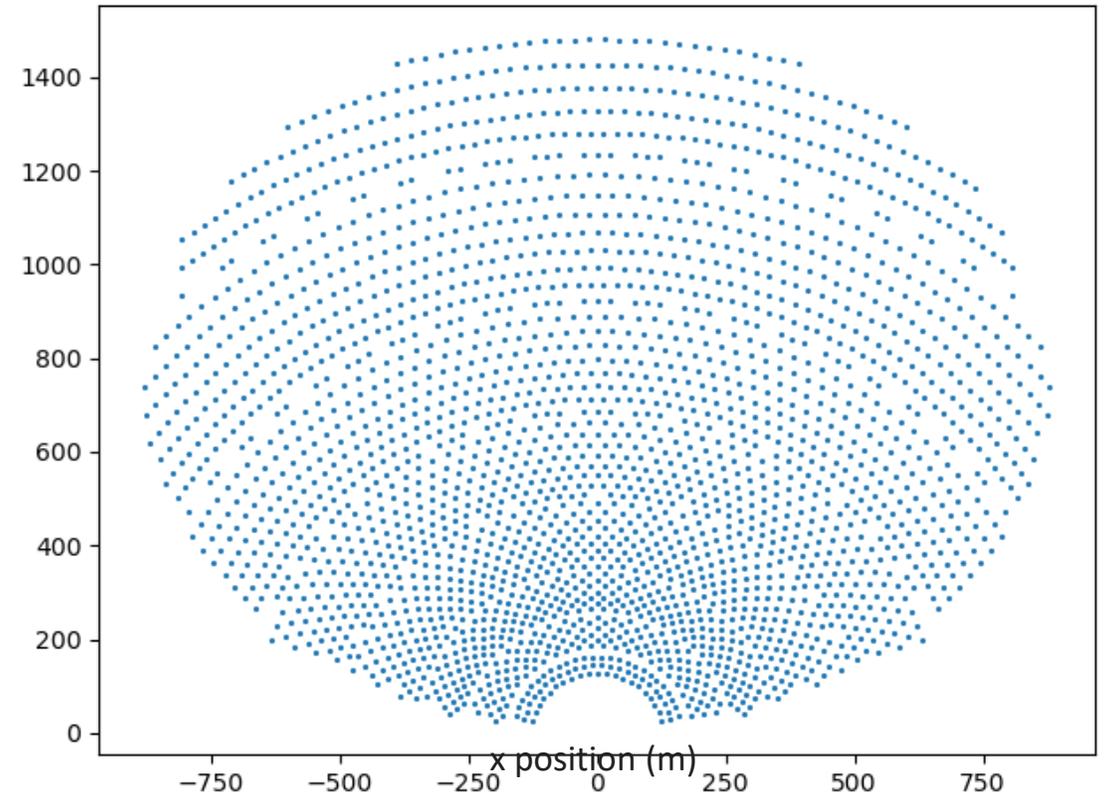
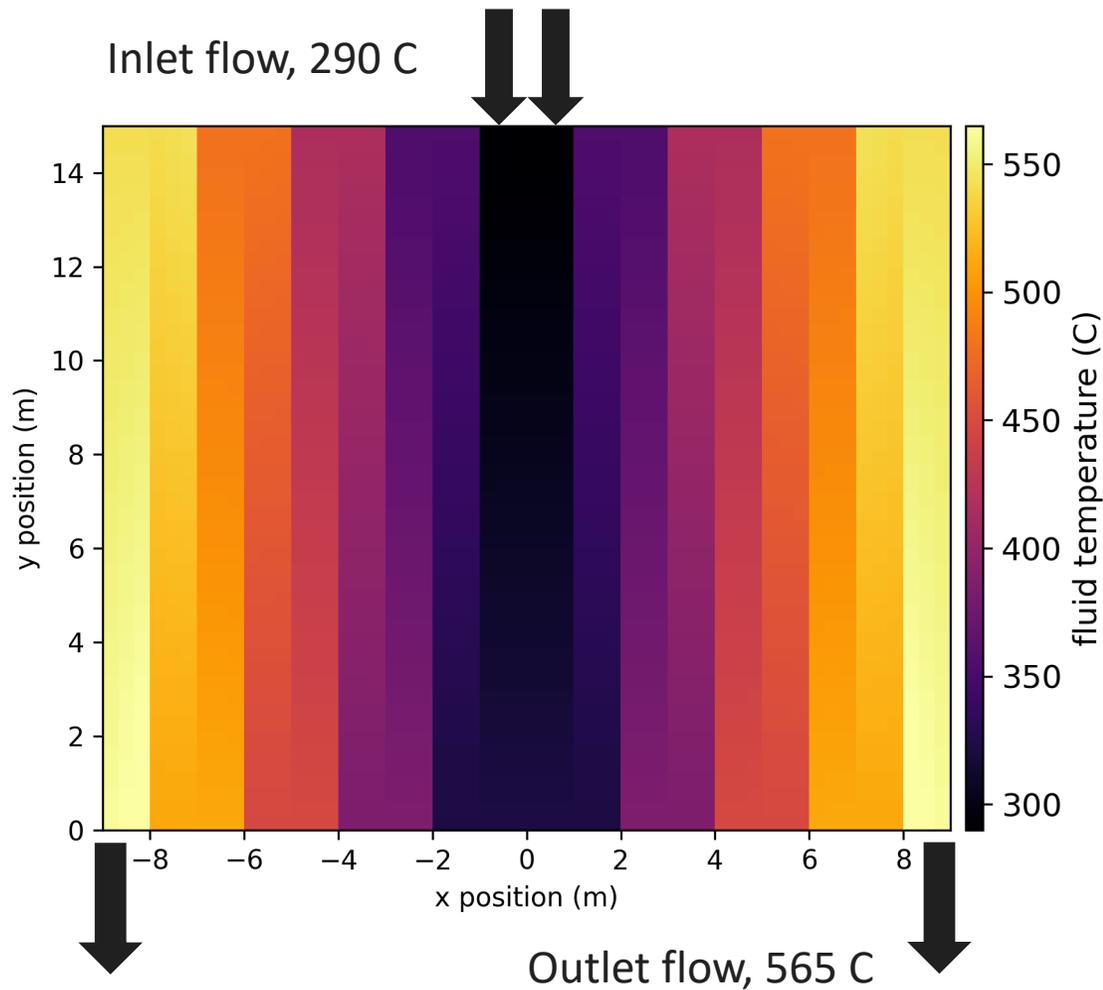


# Receiver thermo-mechanical model determines allowable flux





# Improving a Receiver's Reliable Design Power



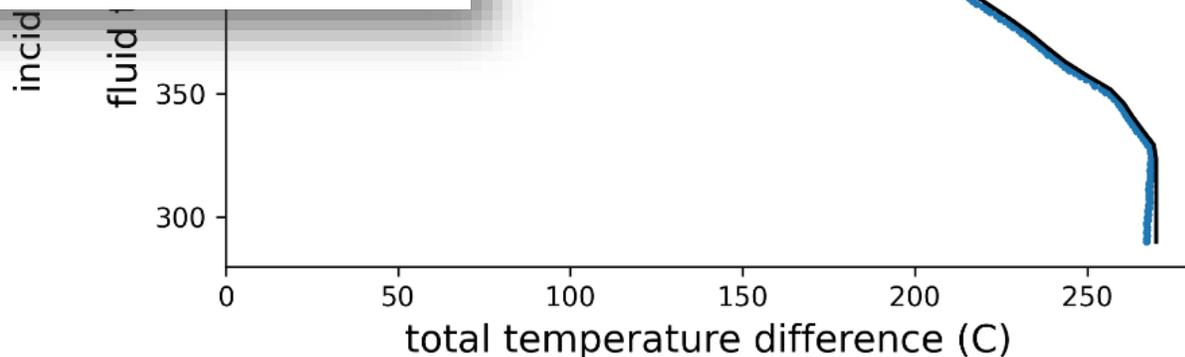
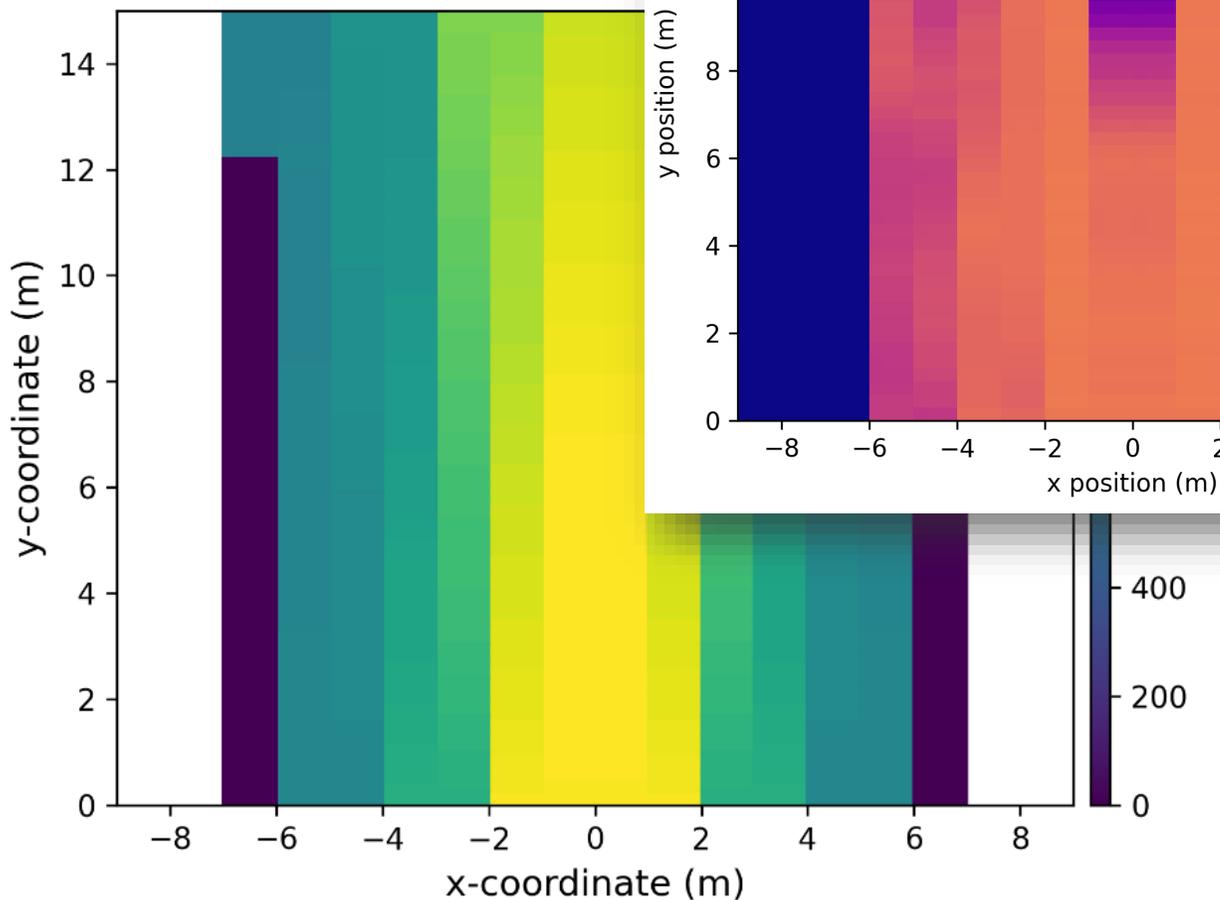
How can we ensure panel reliability while maximizing a receiver's thermal power?



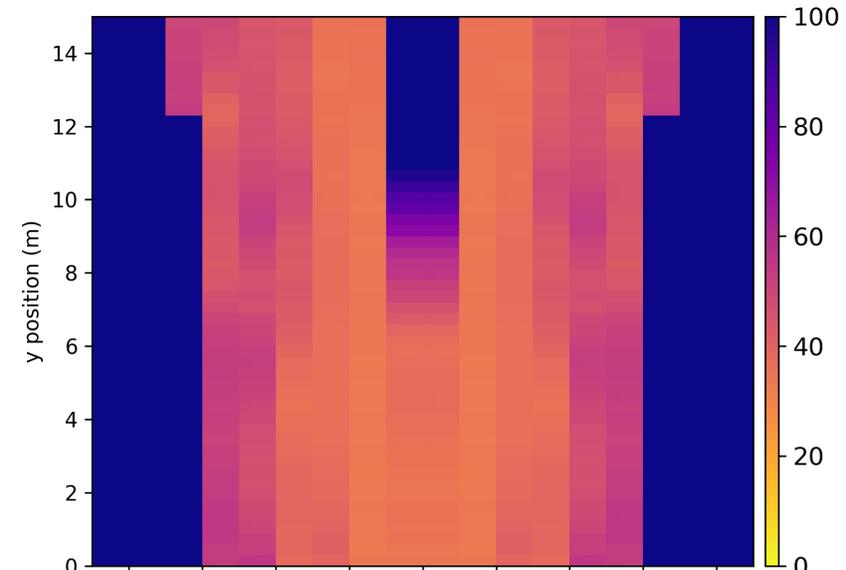
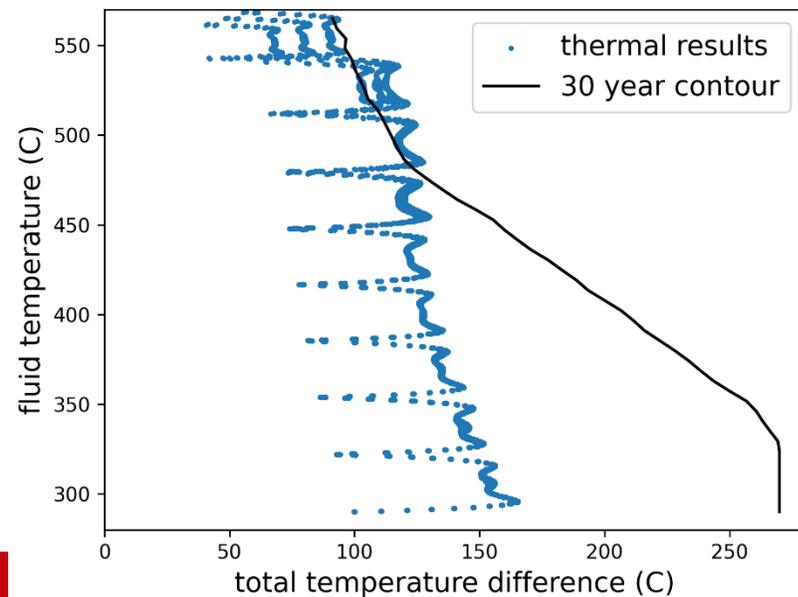
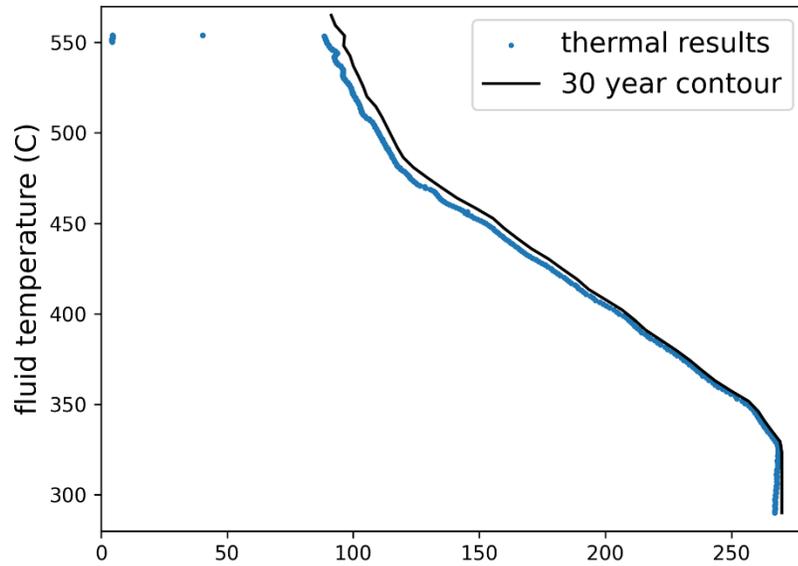
# Ideally Executed Informed Aiming

## Our Goals:

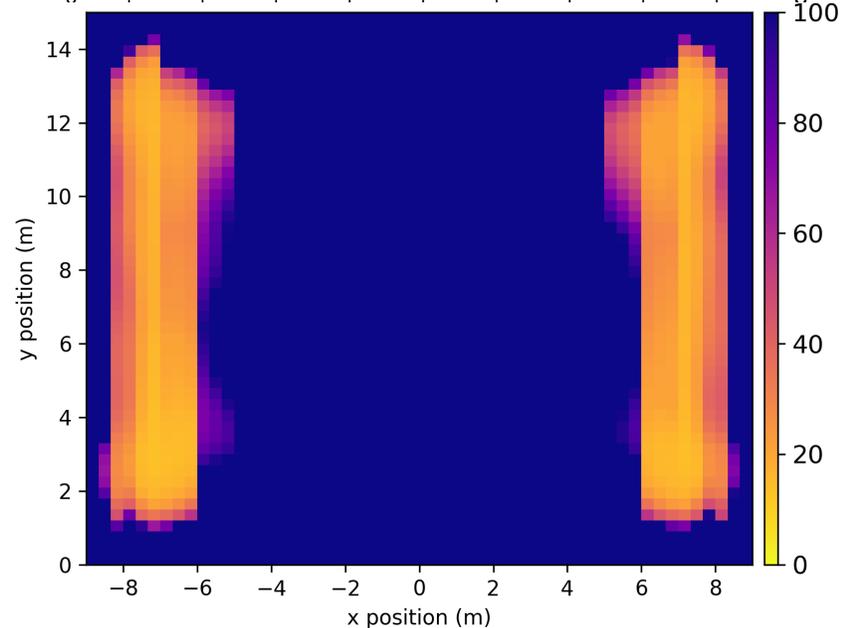
- Investigate creep-fatigue model informed aiming strategies
- fully match actual flux with



# How does a uniform aiming strategy compare?



*Ideally executed informed aiming for 180 MWth case*

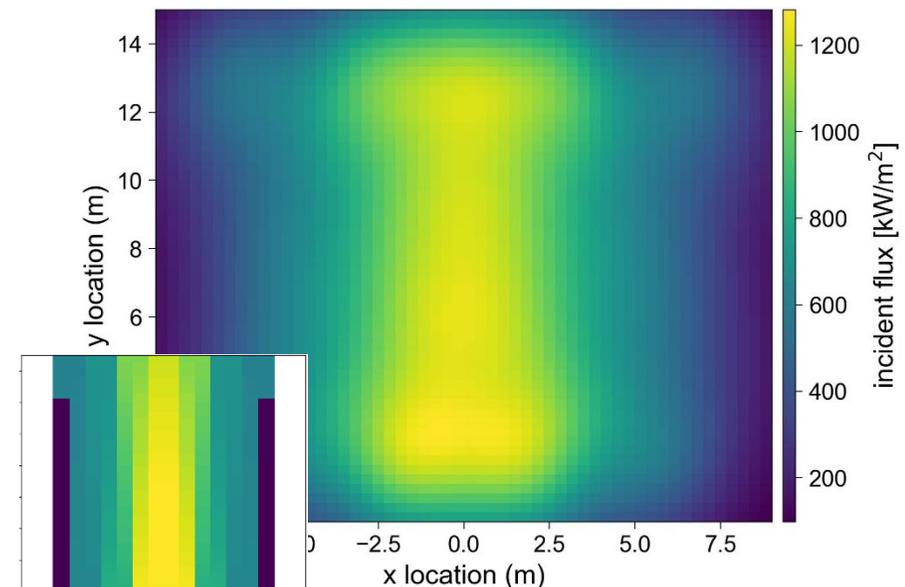
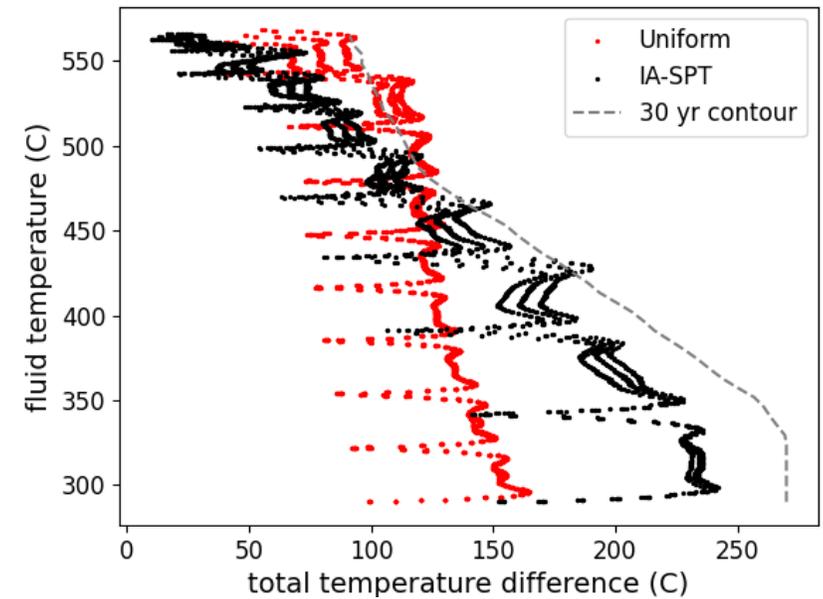
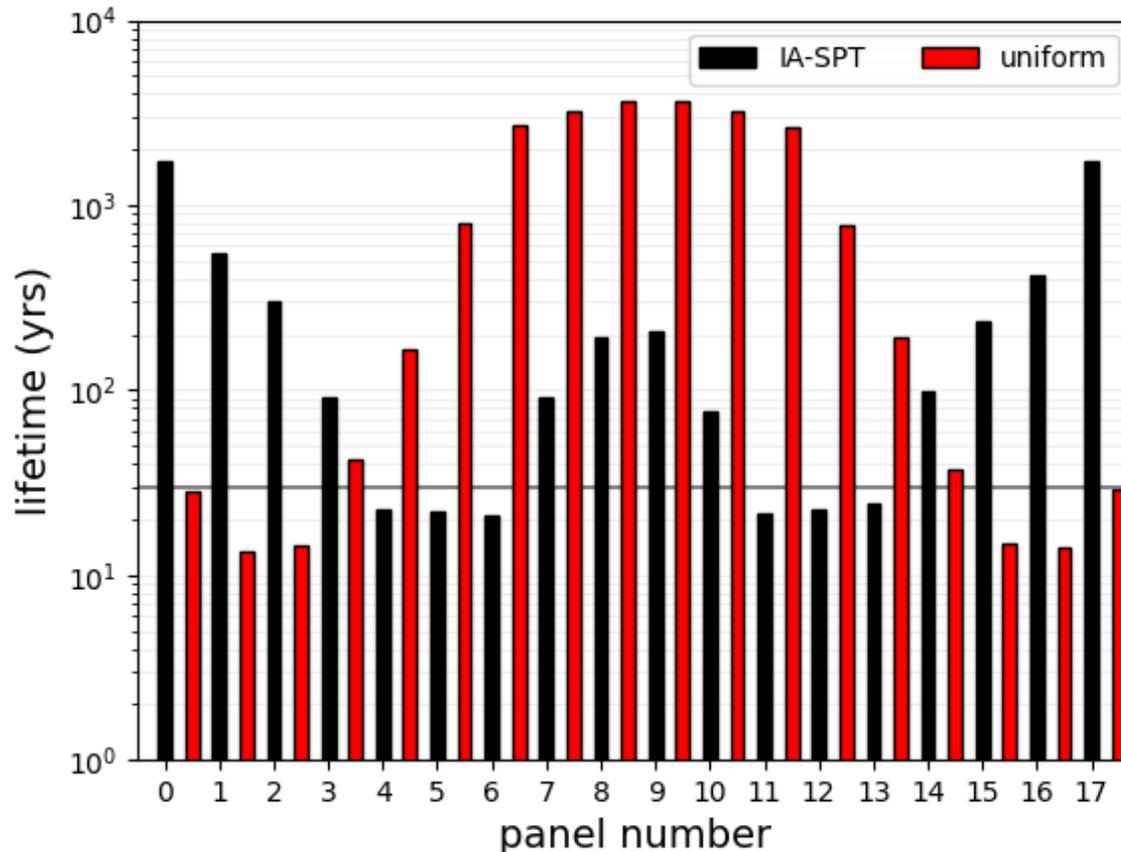


*Uniform aiming via SolarPILOT for 180 MWth case*



# Using Informed Aiming in SolarPILOT – 180 MWth

- Informed SPT aiming uses 140 fewer heliostats
- Informed SPT aiming's first failure at 21 years
- Uniform aiming's first failure at 13.5 years



# Lifetime informed aiming

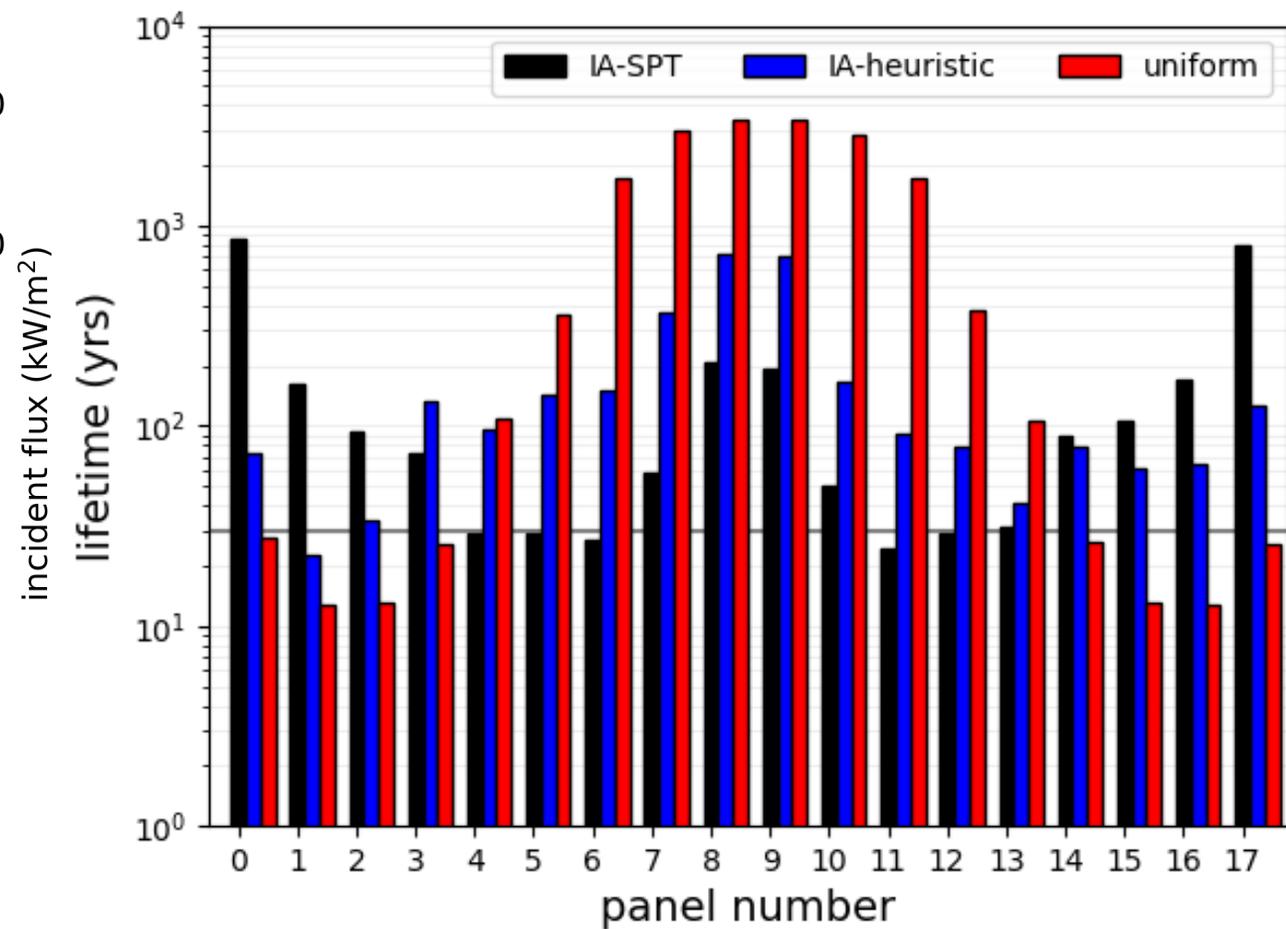
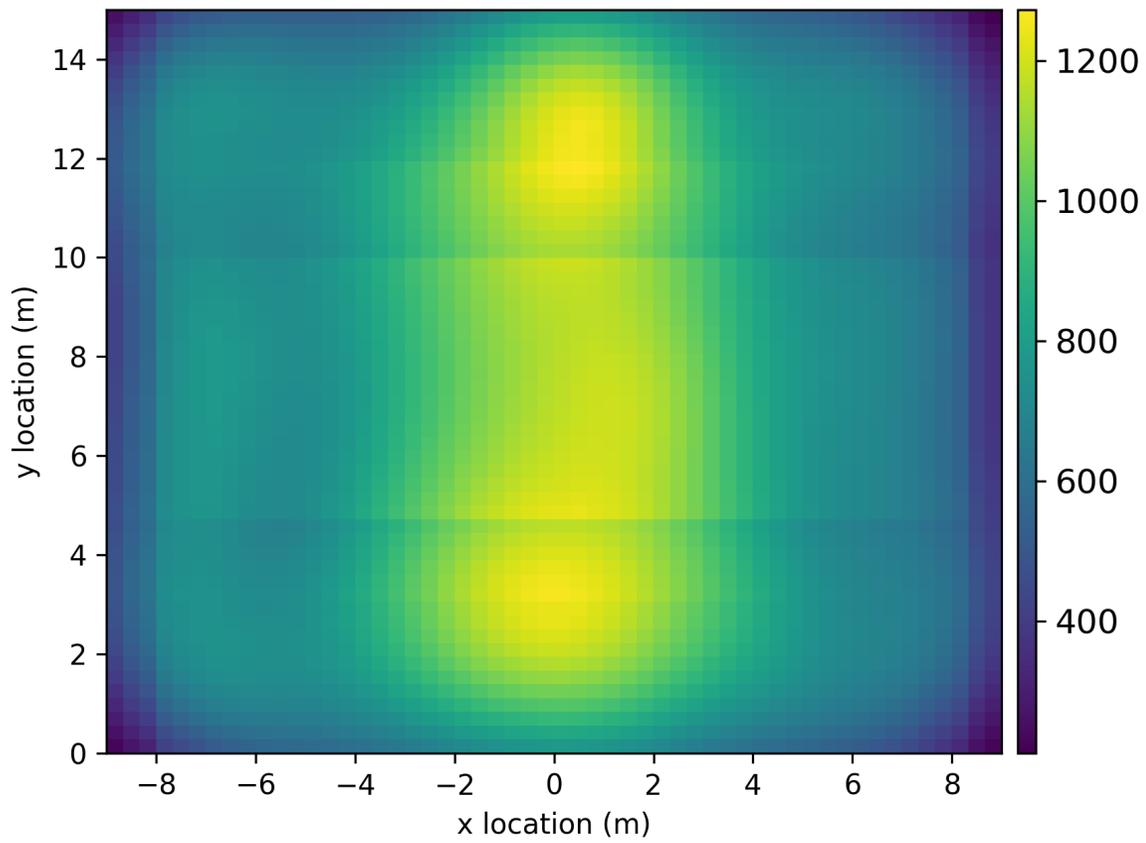
- Select location with maximum LTE metric
- Initially place each image at location of highest difference between ideal and actual flux (slack)
  - large images first
- Solve a lightweight thermal model at regular intervals & check minimum lifetimes
- When the global minimum lifetime falls below a certain value:
  - Consider all placement options by solving thermal model and predicting lifetimes
  - Select location with the highest LTE metric value

$$LTE_{metric} = \sum \frac{\min(LTE_{trig}, \min(LTE_{panel}))}{N_{panels}}$$

- Optical simulation: methods from Heliostat Aimpoint and Layout Optimization Software (HALOS)
- Thermal simulation for image placements: reduced complexity

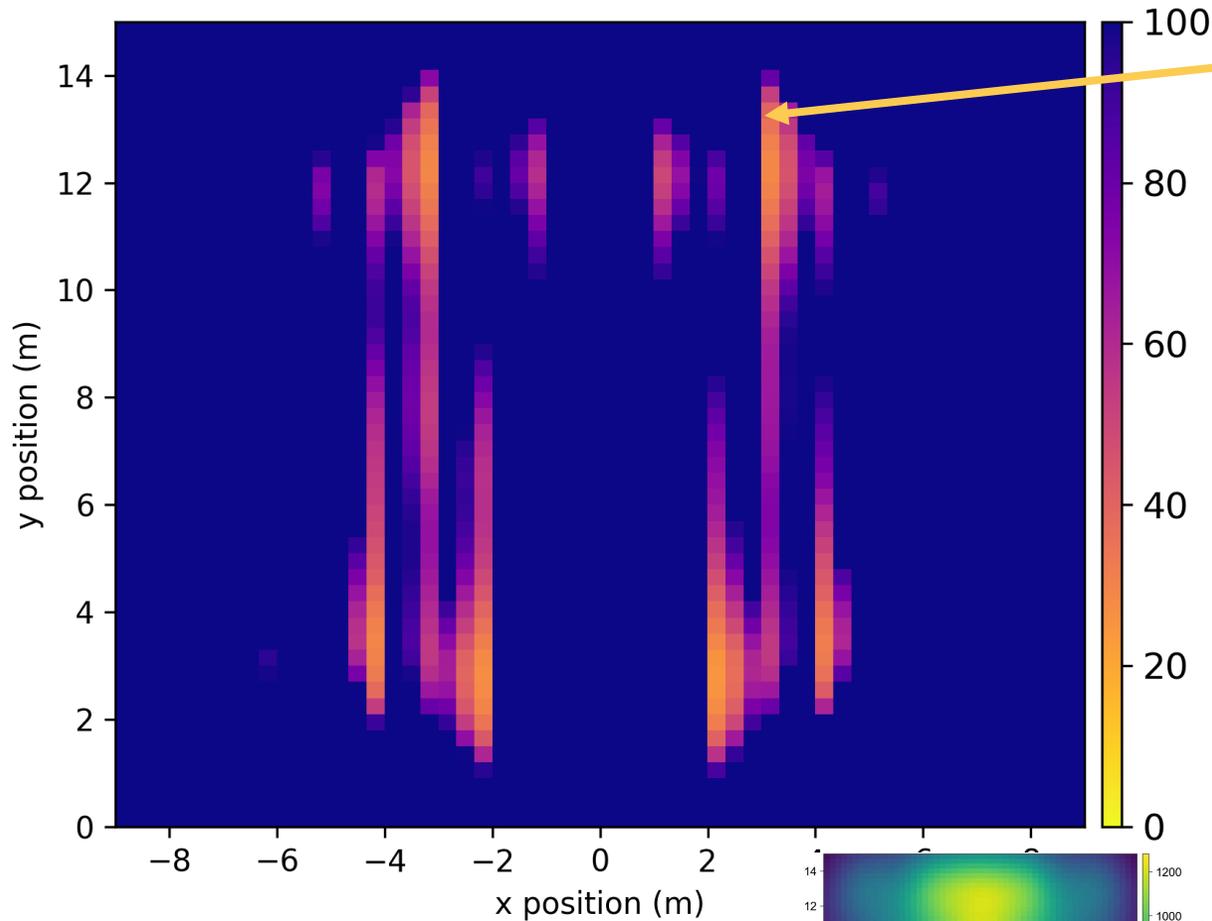


# Informed Aiming Heuristic Performance

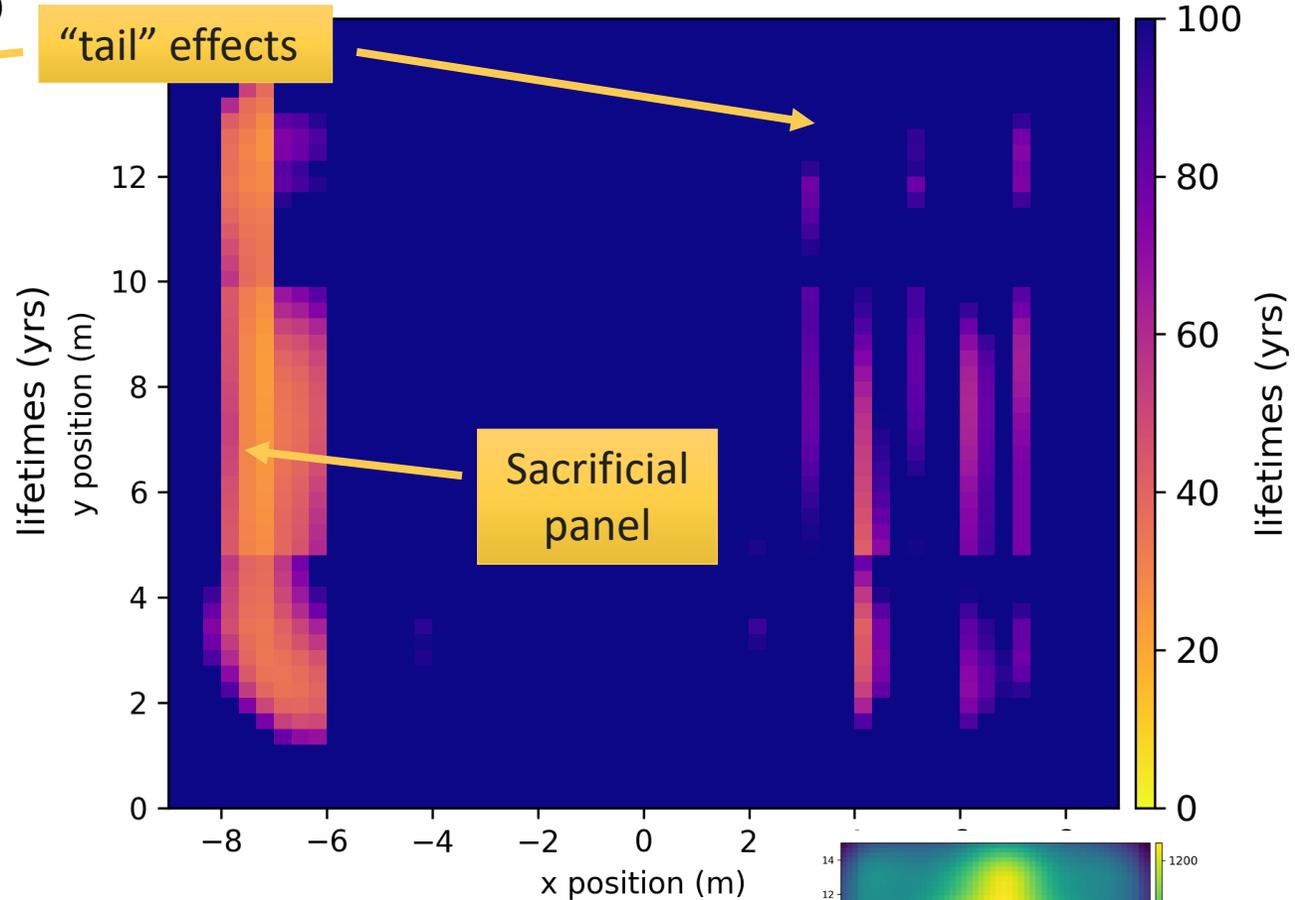
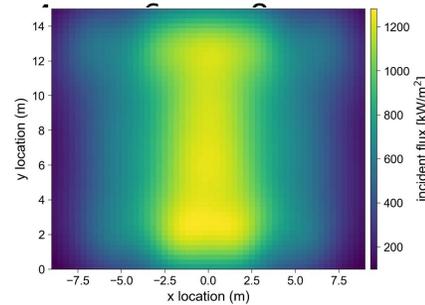




# Informed Aiming Heuristic Performance



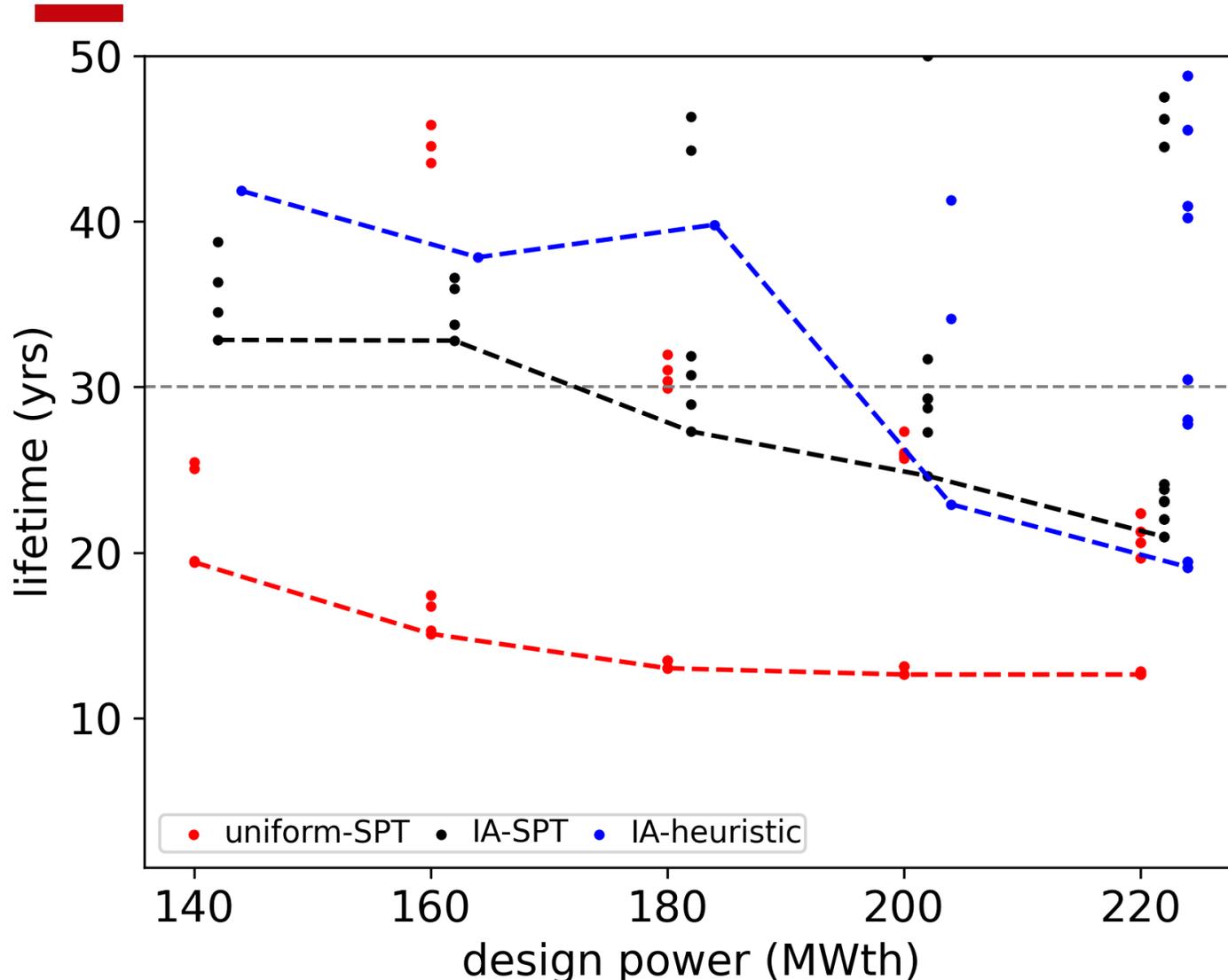
Lifetimes for 200 MWth case with SolarPILOT (SPT) informed aiming



Lifetimes for 200 MWth case with informed aiming heuristic



# Performance over a range of design power levels



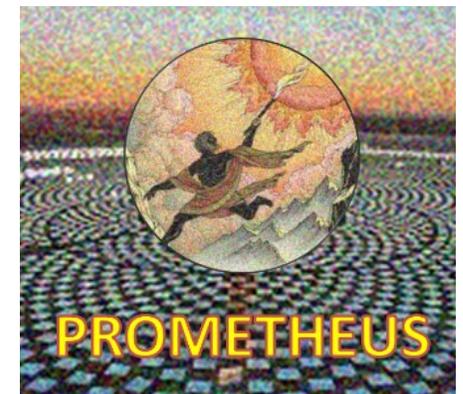
Number of panels below 30 years lifetime

Power (MWth)	Uniform	IA-SPT	IA-Heuristic
140	4	0	0
160	4	0	0
180	5	2	0
200	8	5	1
220	8	6	4

# Summary & Next Steps

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- A software tool is developed to identify optimal aiming strategies for realistic field conditions
- Soiling, availability, nowcasting, and receiver lifetime effects are incorporated
- A heuristic algorithm was developed, serving as baseline for day-ahead aiming strategy
- Further development needed for real-time optimization
- Multi-objective optimization will balance:
  - Optical efficiency
  - Drive tracking power requirements and failures
  - Receiver lifetime
  - Cleaning frequency



**Thank you for  
your attention!**



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