# Algorithms, interfaces and frameworks for efficient cross-facility scheduling

Pep Colomé, on behalf of the IEEC team

*Thanks to all contributors from the different projects and missions*

Institute of Space Studies of Catalonia (IEEC)
Institute of Space Sciences (ICE, CSIC)

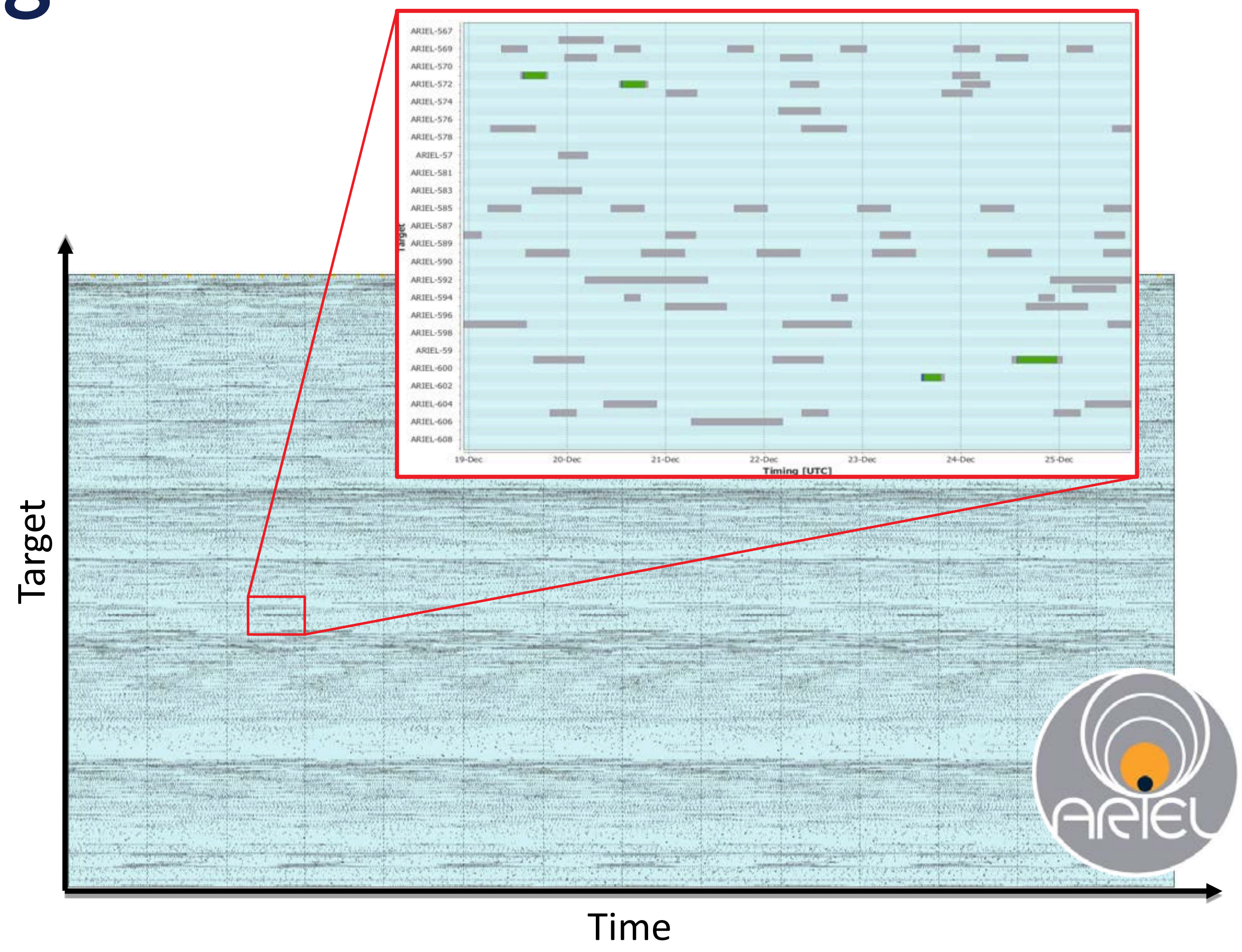
ESA/ESO SCIOPS Workshop 2019

# Outline

- STARS framework
  - Features
  - Perfomance metrics
  - Optimization strategies & algorithms
  - ATP GUI
- Scheduling Applications
  - Single telescope: ARIEL-ESA, CARMENES, TJO@OAdM
  - Observatory with multiple sites and sub-arrays: CTA
  - Multi-observatory & MM
    - o Coordinated planning: CTA&SKA, CTAN&S+GW
    - o Coordinated follow-up planning: PLATO-ESA, GW
  - Multi-Messenger coordination Platform

# Why an automatic scheduling tool?

- Why an automatic scheduling tool?
  - Complexity of the problem
  - Easy simulation for different scenarios before the mission
  - Fast adaptability to changes during the mission
- ESA-ARIEL survey in numbers
  - Survey ~1000 exoplanets (from ~2000 available)
  - 4 years mission lifetime (3.5 years survey)
  - 1~20 events per target
  - ~200 observable events for each target
  - ~ 120 events at the same time
  - ~13.5k total requested observations (for ~2000 targets)
  - 2.5k~3.5k observations in the final plan
  - About e^4800 possible combinations




**Huge amount of possible combinations!**

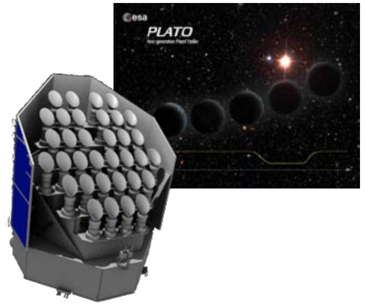
Searching all the options for the best plan would be infeasible

# Scheduling application framework

**STARS** framework:

*Scheduling Technologies for Autonomous Robotic Systems*

- Goals
  - Tool to automatically plan observations and operations
  - Optimize the plan to fulfill science goals
  - Analyze mission scenarios:
    - Number of targets observed
    - Challenging targets and observation strategies
    - Impact of different operational constraints
    - …
  - Re-usable software for diferent projects and missions



# Scheduling application framework

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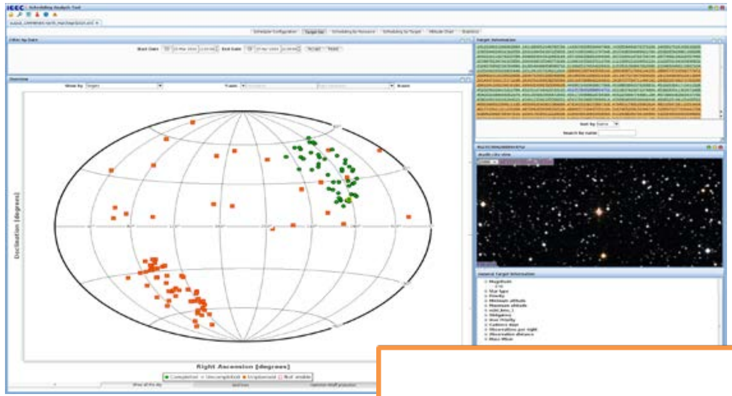
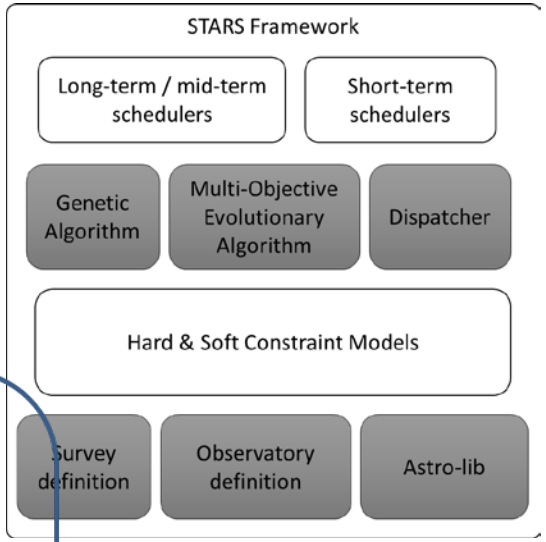





**ATP**
**Analysis Tool for Planning**
*Configuration + Visualization*
Java Front-end

**STARS**

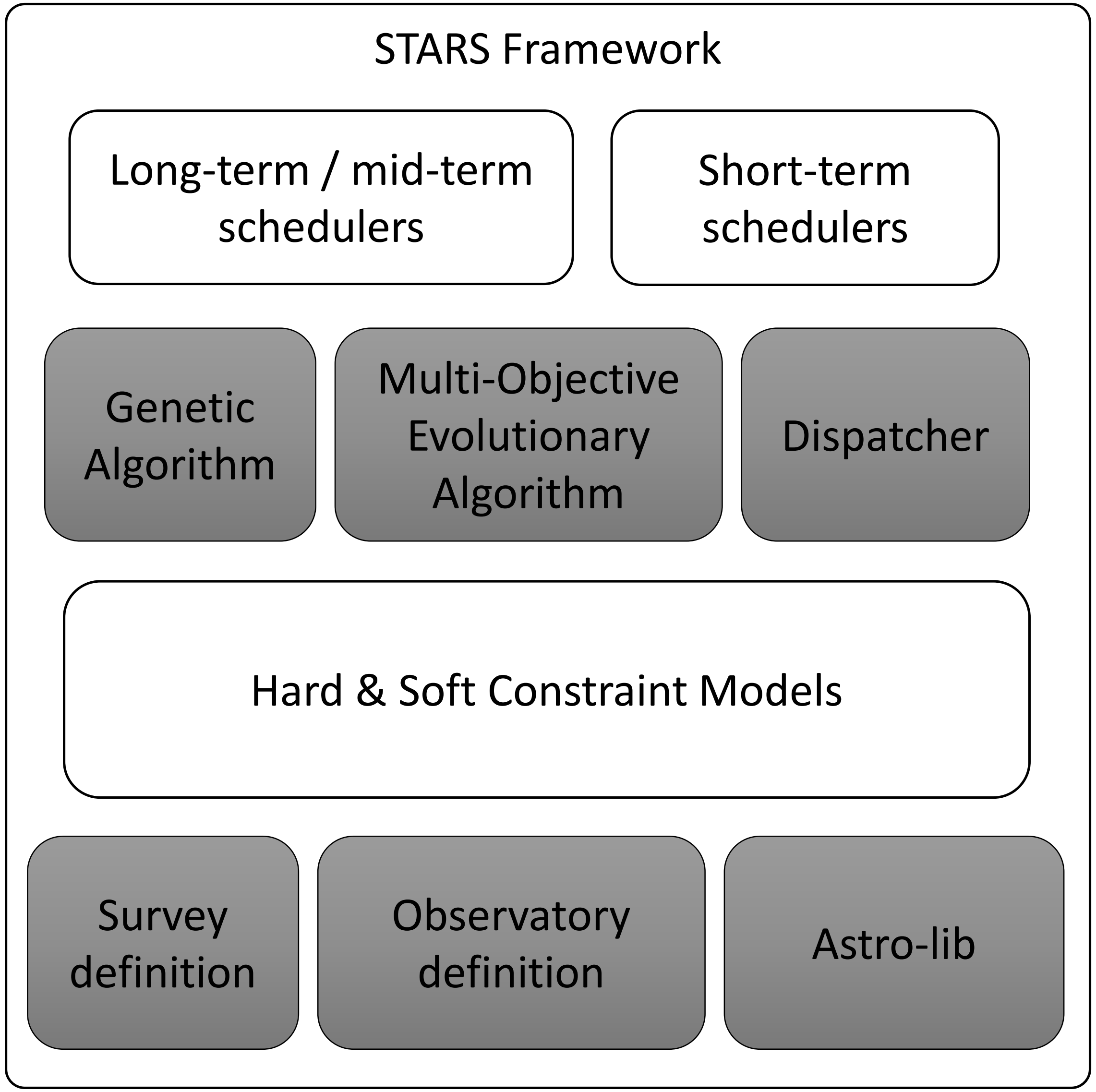
XML files & DB-SQL (proposals, weather data, etc.)

Astro-lib
AI Algorithms
Constraint models
C++

**MISSION I/F**
(OCS, TCS, ICS IOSDC-MOC)

# Features

- Libraries
  - Definition of the survey: objects to be observed, features of the objects
  - Definition of the observatory: location, number of telescopes, type of telescopes
  - Astronomical calculations: object coordinates, object elevation, Sun and Moon position, Moon phase
  - Long- and mid-term schedulers based on Evolutionary Algorithms, and for a short-term scheduler a dispatcher using astronomy-based heuristics
- I/O based on XML files (similar to RTML format)



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    + <MeteoNonObservablePeriods>
    </Observatory>
  + <Configuration>
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  + <Schedule>
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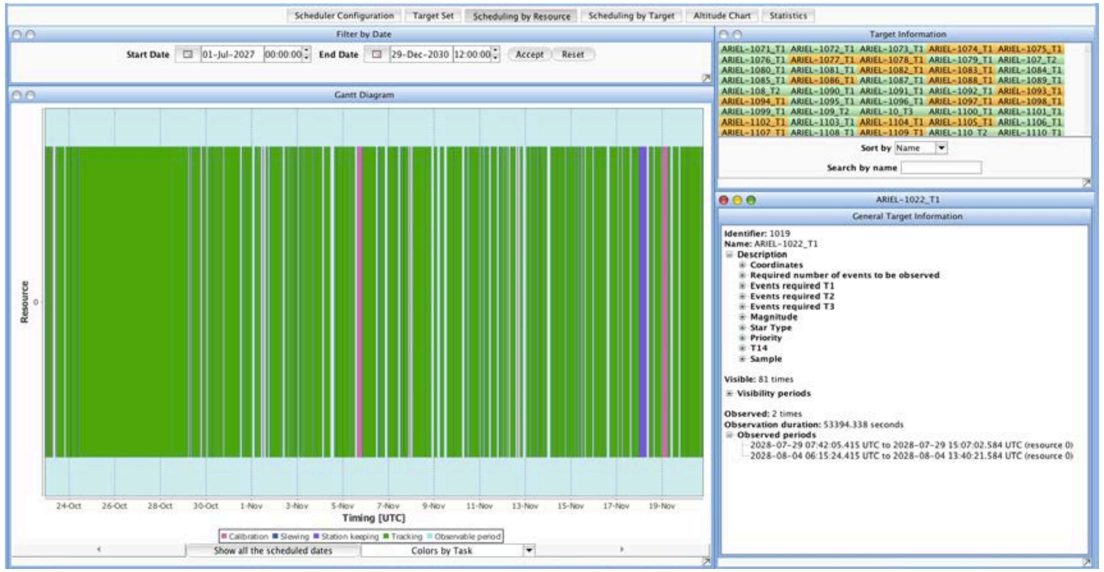
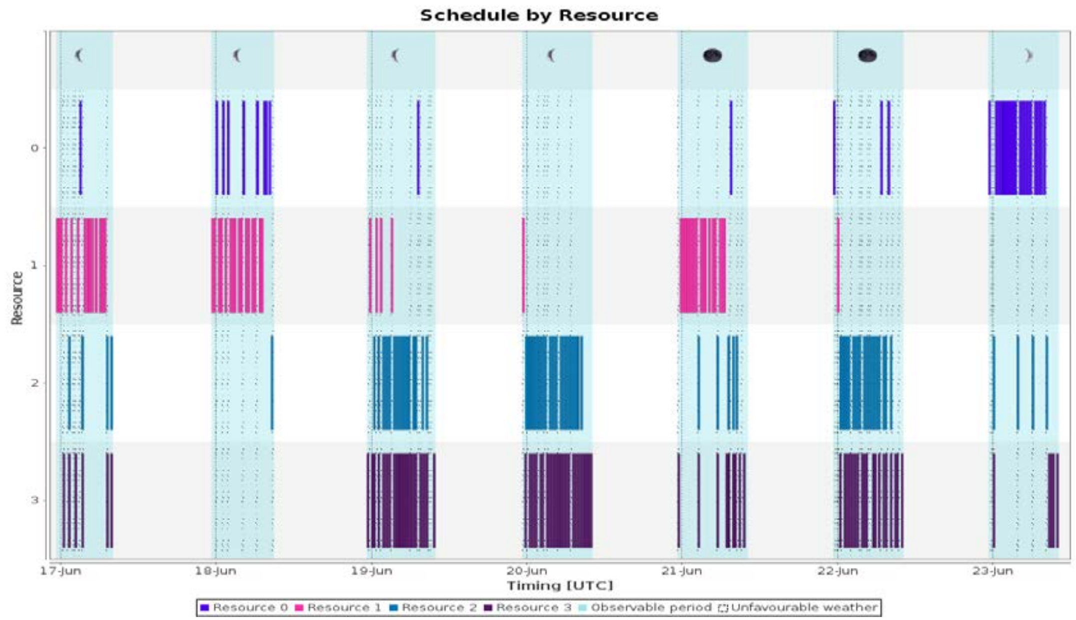
```

# Performance metrics

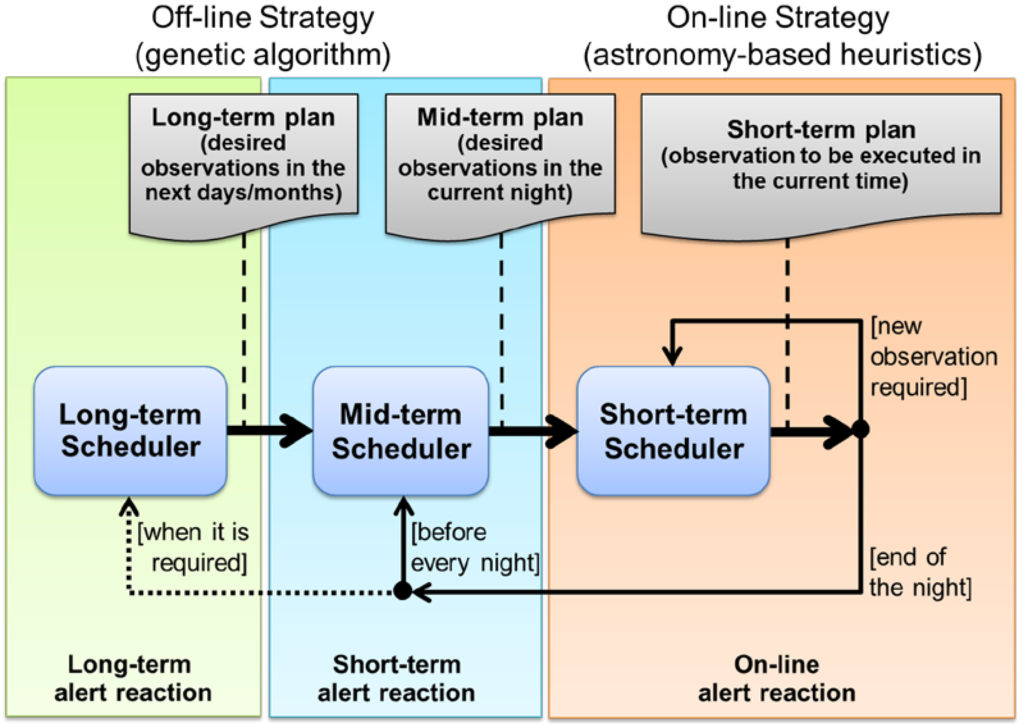
- Observing time optimization
  - The **time** in the schedule during which the **telescope** is **observing** objects should be maximized
- Optimization of scientific return
  - The **observation of completed targets** should be maximized in order to increase the scientific efficiency of the mission
  - **Observation of the priority targets** should be promoted
  - **Observation deviation** to ensure that all targets with the same priority will have a proper share of assigned observing time
  - **Observing cadence** according to the observation strategy



# Optimization strategies

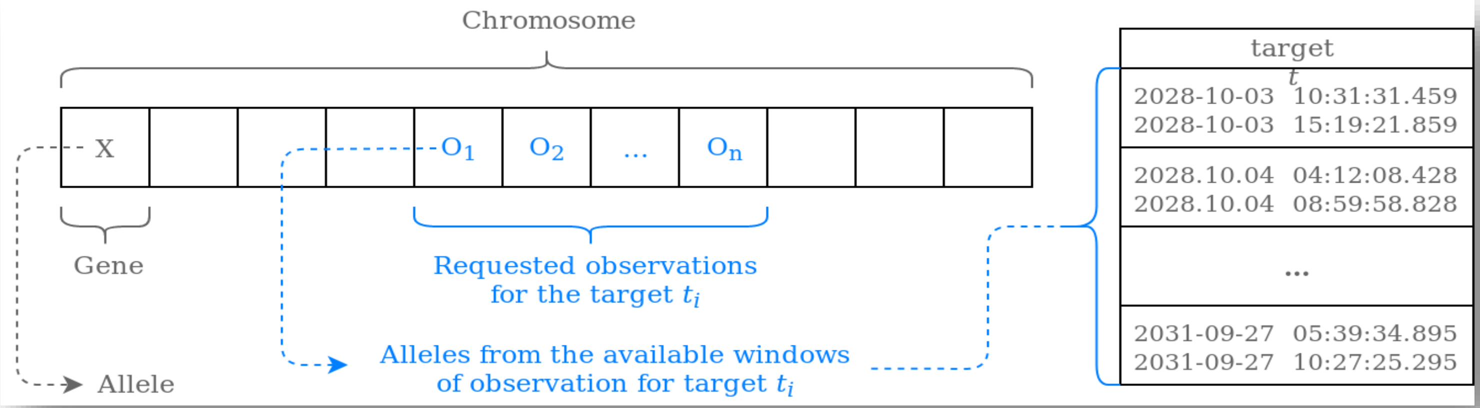
- Off-line ➔ Long-term and Mid-term schedulers
  - Time interval according to hard constraints that can be predicted
- On-line ➔ Short-term scheduler
  - It considers all constraints and adapts the mid-term plan to react to immediate circumstances




| Constraint |
|---|
| **Hard Constraints** |
| ➔ Priorities |
| ➔ Night & Elevation |
| ➔ Moon influence |
| ➔ Visibility duration |
| ➔ Pointing |
| ➔ Overlapping |
| ➔ Overhead time |
| ➔ Environmental conditions |
| **Soft Constraints** |
| ➔ Observing time |
| ➔ Observation deviation |
| ➔ Observing cadence |

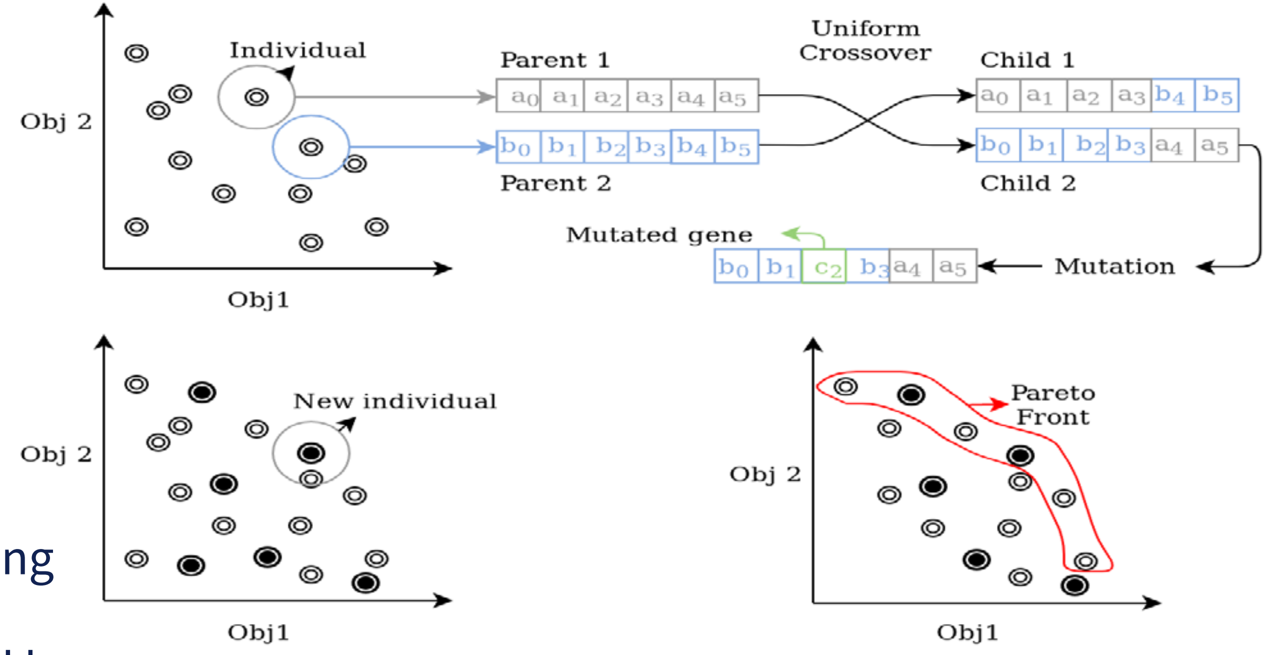
# Optimization algorithms

- Scheduling optimization
  - A global optimization problem
  - Using local optimization algorithms significantly limits the search space for the best solution
  - Multiple objectives to optimize (completed targets, observation time and the total slew time)
  - Different tasks that have to be included in the final plan (target observations, calibrations, housekeeping, and slew times)
- Problem representation - Genetic structure
  - Set of targets to observe T = {t1, t2, …, tT }
  - Set of requested observations for each target
  - Candidate solution:



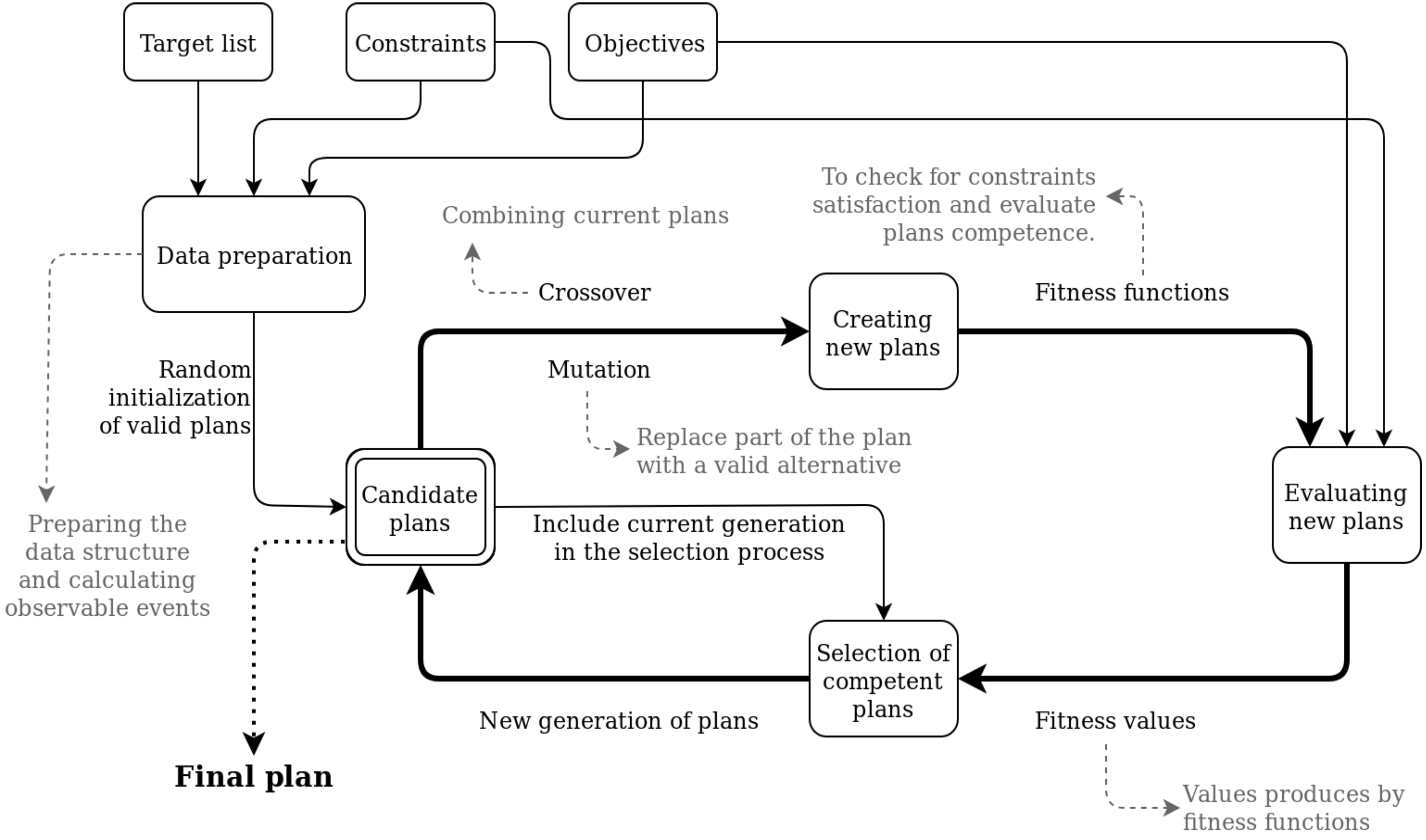
# Optimization algorithms

- Scheduling algorithm
  - Evolutionary Multi-objective Optimization (EMO or MOEA)
    - Combines (crossover, mutation) a set of candidate solutions to explore the parameter space of the problem
  - Non dominated sorting genetic algorithm II (NSGA-II)
    - Few objectives
    - Not a complicated Pareto Front
      - Solutions not dominated by others
    - Loads of local minimums
    - Crowding distance consideration
  - Astronomical heuristics for short-term planning
  - On-going work
    - Library under testing: PaGMO, developed by ESA for parallel optimization
    - Constraint propagation and ACO under exploration

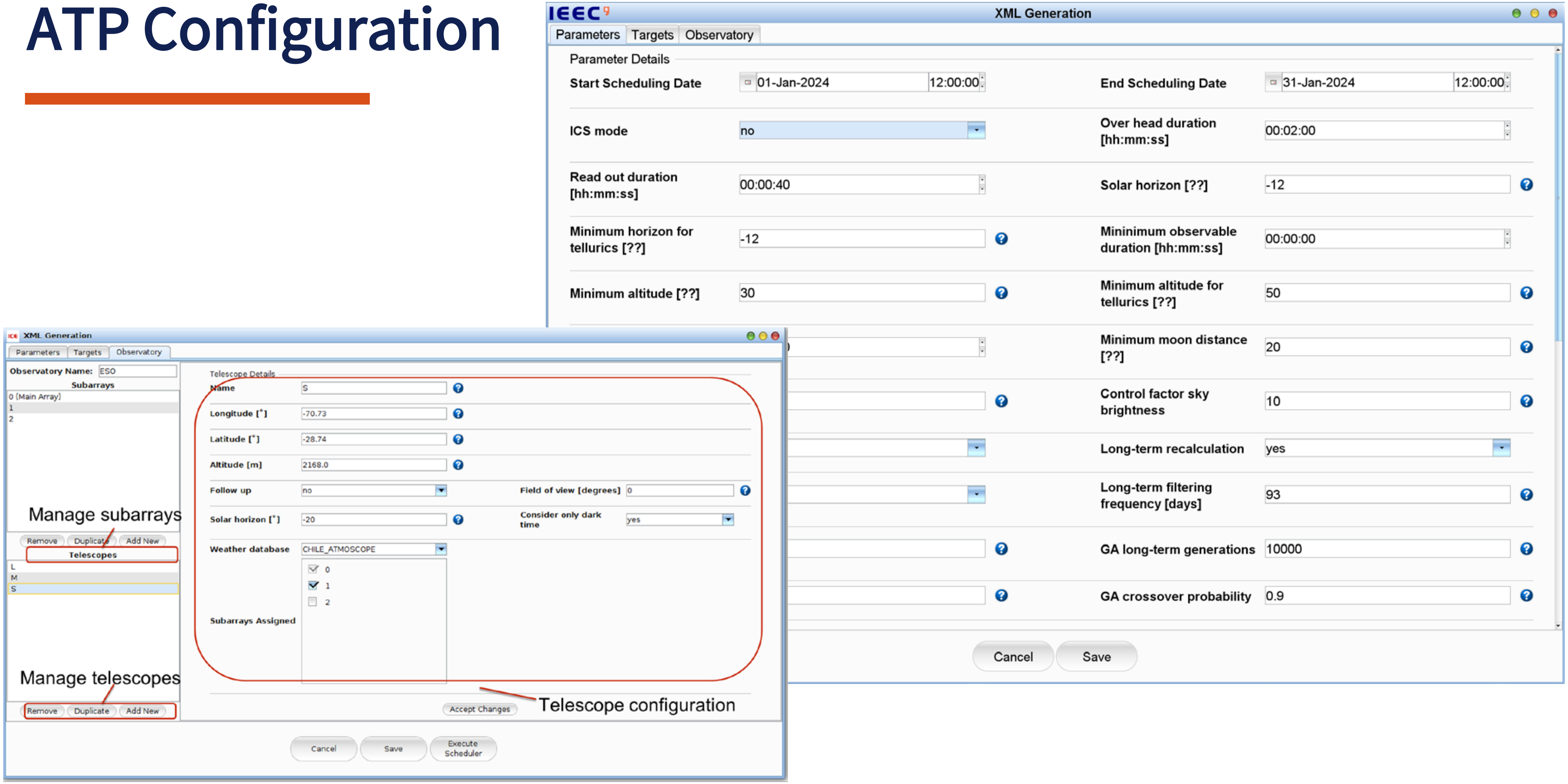


# Optimization algorithms

- Optimization process based on AI Algorithms

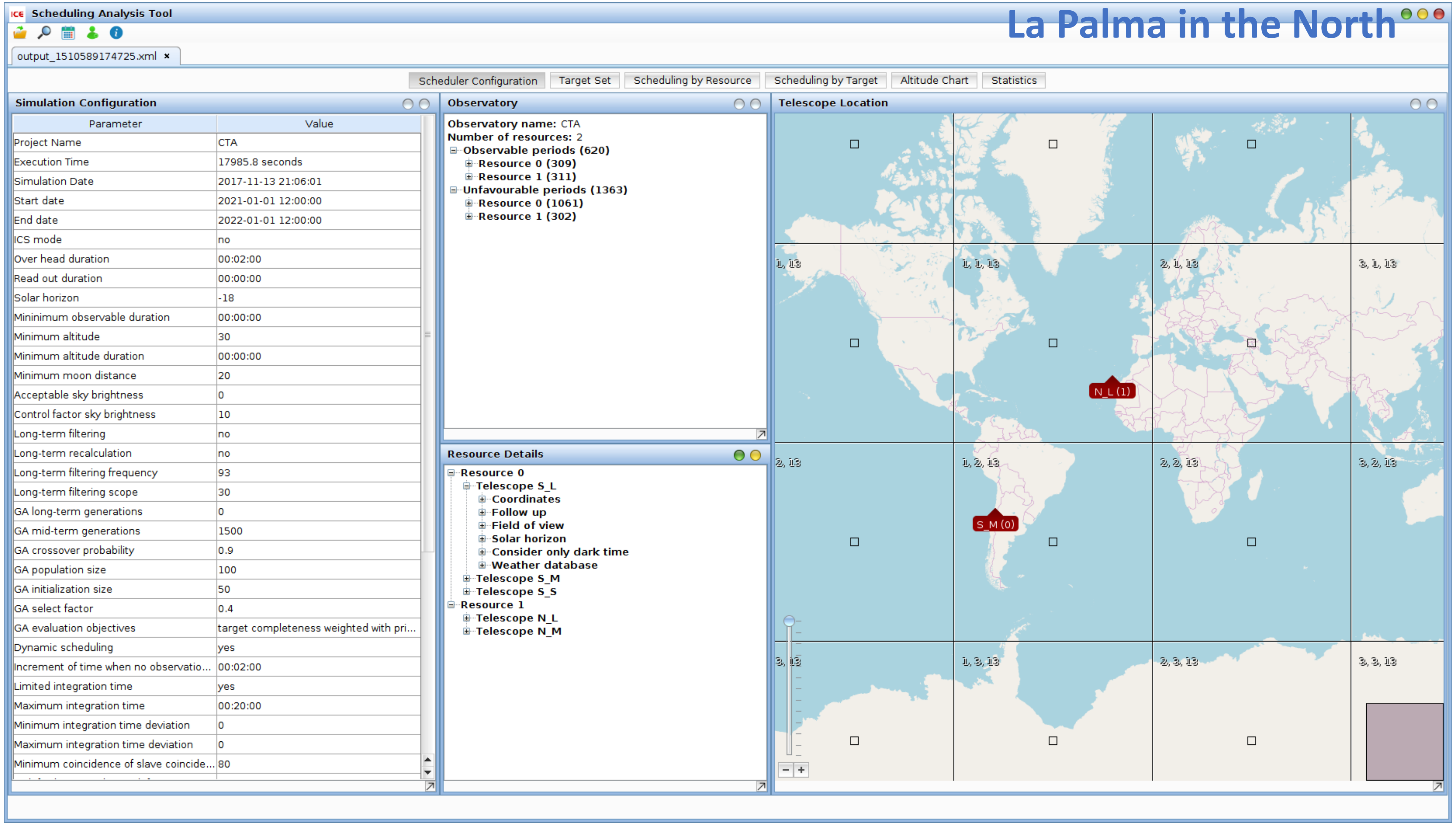


# ATP Configuration



# ATP GUI for STARS

**Two sites: Paranal in the South and La Palma in the North**



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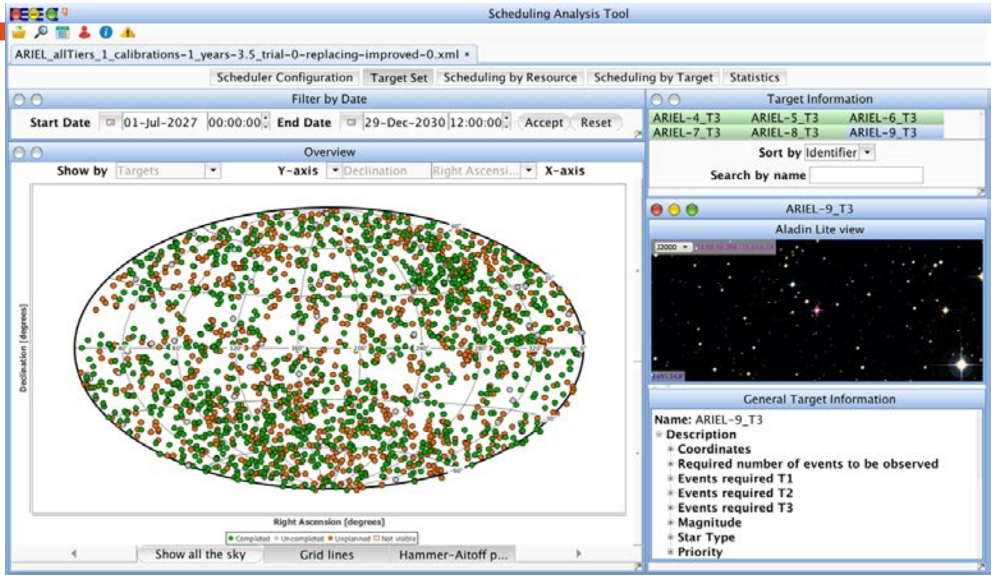


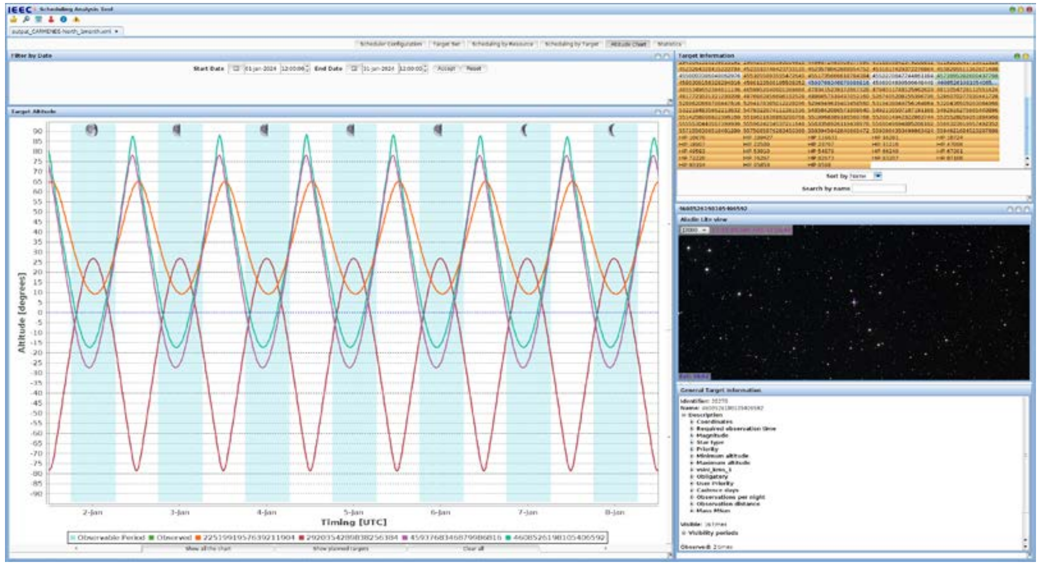


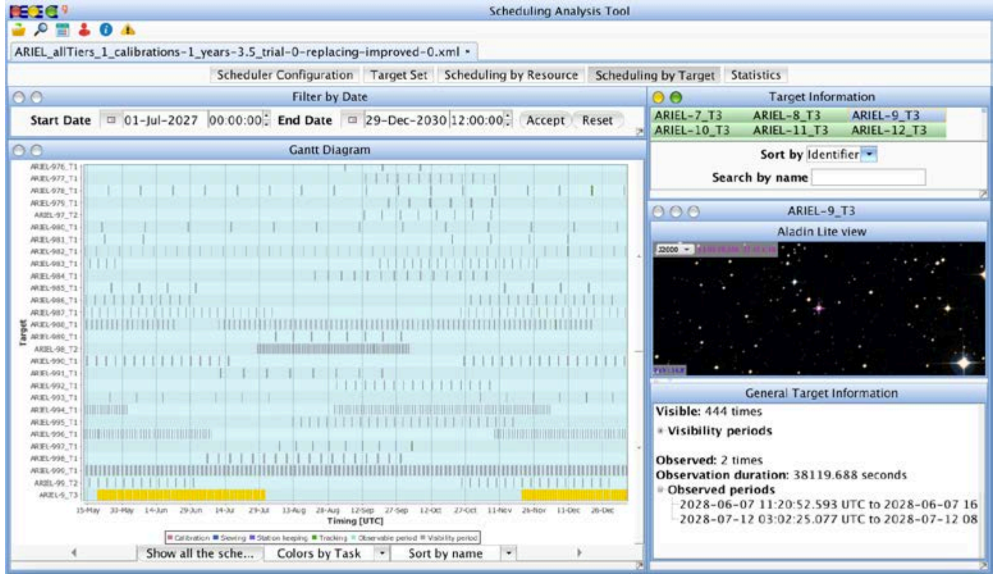


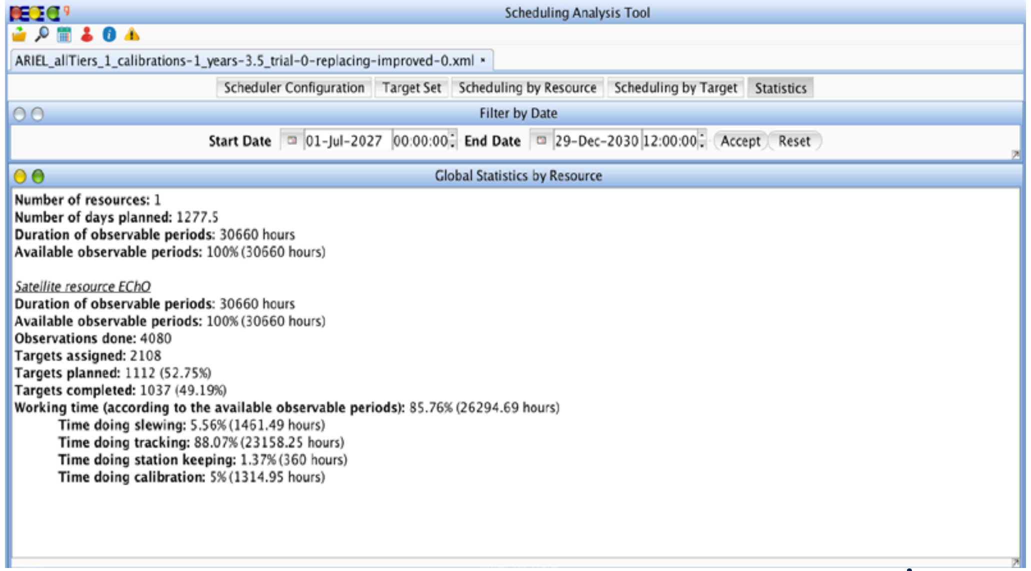

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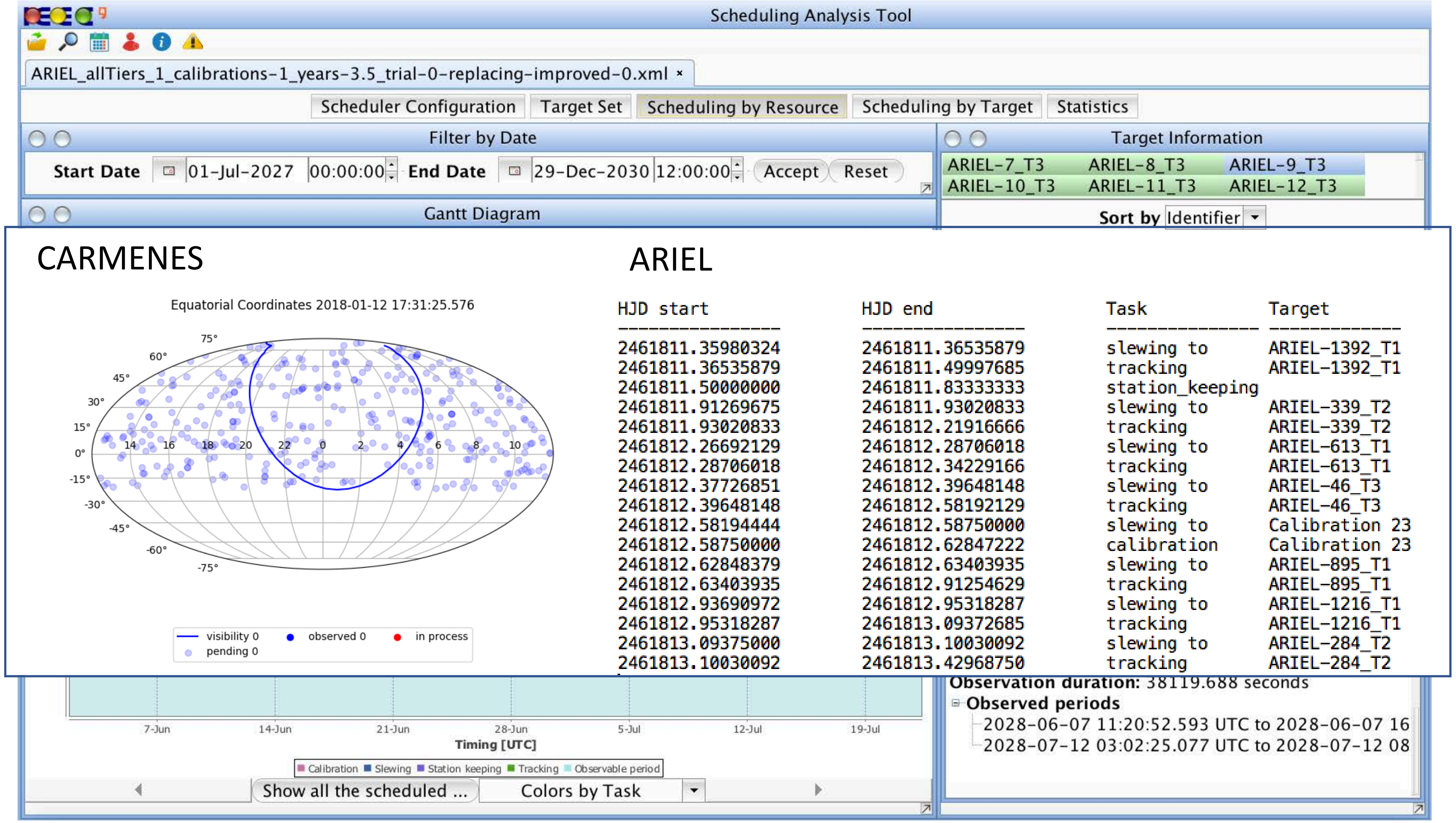


| HJD start | HJD end | Task | Target |
|---|---|---|---|
| 2461811.35980324 | 2461811.36535879 | slewing to | ARIEL-1392_T1 |
| 2461811.36535879 | 2461811.49997685 | tracking | ARIEL-1392_T1 |
| 2461811.50000000 | 2461811.83333333 | station_keeping | |
| 2461811.91269675 | 2461811.93020833 | slewing to | ARIEL-339_T2 |
| 2461811.93020833 | 2461812.21916666 | tracking | ARIEL-339_T2 |
| 2461812.26692129 | 2461812.28706018 | slewing to | ARIEL-613_T1 |
| 2461812.28706018 | 2461812.34229166 | tracking | ARIEL-613_T1 |
| 2461812.37726851 | 2461812.39648148 | slewing to | ARIEL-46_T3 |
| 2461812.39648148 | 2461812.58192129 | tracking | ARIEL-46_T3 |
| 2461812.58194444 | 2461812.58750000 | slewing to | Calibration 23 |
| 2461812.58750000 | 2461812.62847222 | calibration | Calibration 23 |
| 2461812.62848379 | 2461812.63403935 | slewing to | ARIEL-895_T1 |
| 2461812.63403935 | 2461812.91254629 | tracking | ARIEL-895_T1 |
| 2461812.93690972 | 2461812.95318287 | slewing to | ARIEL-1216_T1 |
| 2461812.95318287 | 2461813.09372685 | tracking | ARIEL-1216_T1 |
| 2461813.09375000 | 2461813.10030092 | slewing to | ARIEL-284_T2 |
| 2461813.10030092 | 2461813.42968750 | tracking | ARIEL-284_T2 |

# ATP GUI & Scheduler I/F



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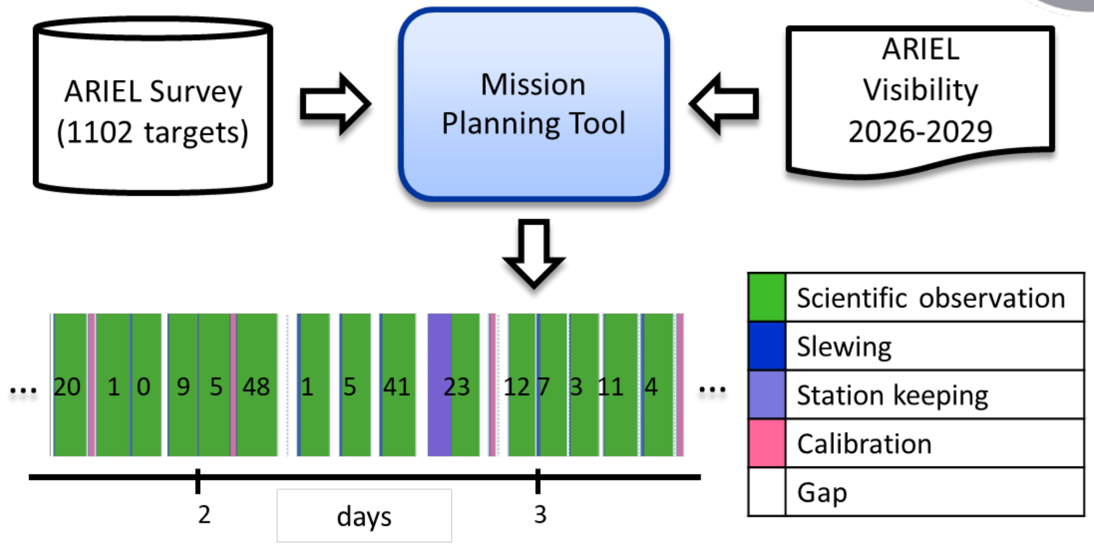
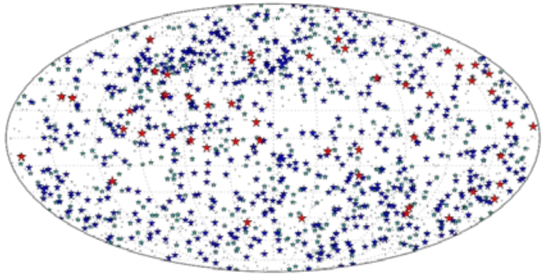
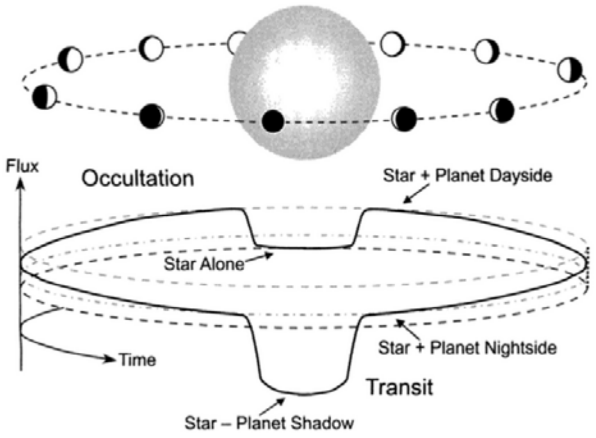
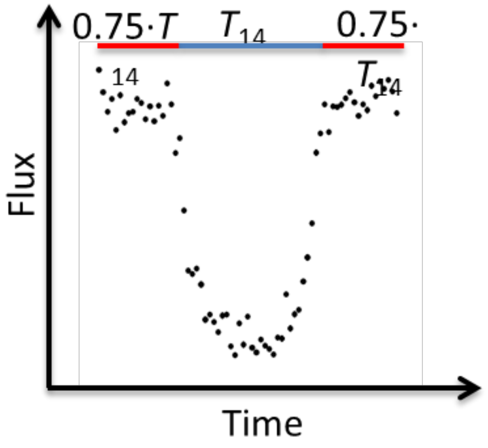
# ESA-ARIEL

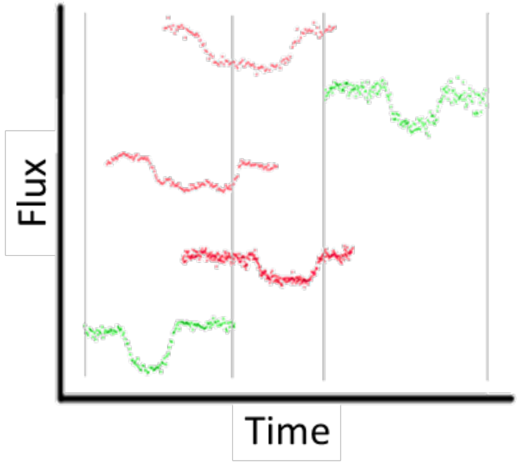
- The Atmospheric Remote-Sensing Infrared Exoplanet Large-Survey (ARIEL), ESA M4 mission (launch 2028)
- Application focused on the mission operations planning ➔ Long-term
- Singular **strategy: time-critical events**





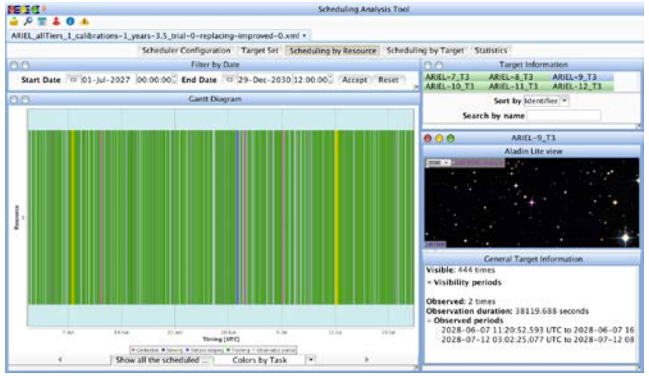



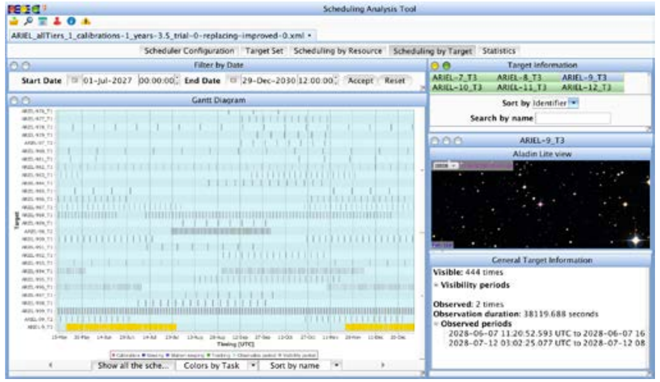



# ESA-ARIEL

- Simulation results - Mission planning tool executions

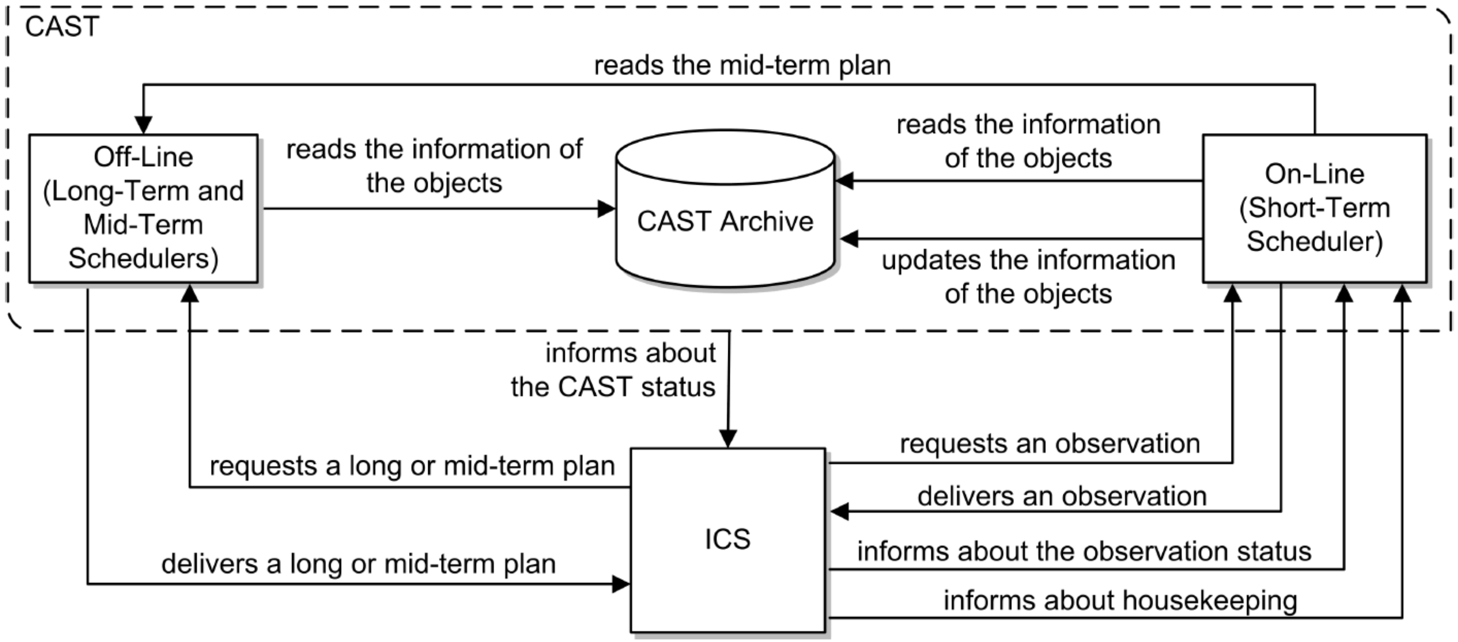
| Mission lifetime period (Years from launch) | Planned targets | Working time | | | Waiting time |
|---|---|---|---|---|---|
| | | On targets | Slewing | Cal. + S. Keep. | |
| 0.5 – 4.0 (No phase curves) | 1112±8 | 67.85±0.31% (20804±96 h) | 3.96±0.03% (1214±10 h) | 5.46% (1675 h) | 22.73±0.32% (6968±99 h) |
| 0.5 – 4.0 (Phase curves) | 1112±8% | 68.46±0.31% (20991±94 h) | 3.90±0.03% (1197±8 h) | 5.45% (1672 h) | 22.18±0.31% (6801±02 h) |
| 0.5 – 4.0 (Phase curves + rep.) | 1115±9% | 75.75±0.18% (23224±56 h) | 4.79±0.03% (1467±11 h) | 5.45% (1672 h) | 14.01±0.19% (4296±57 h) |



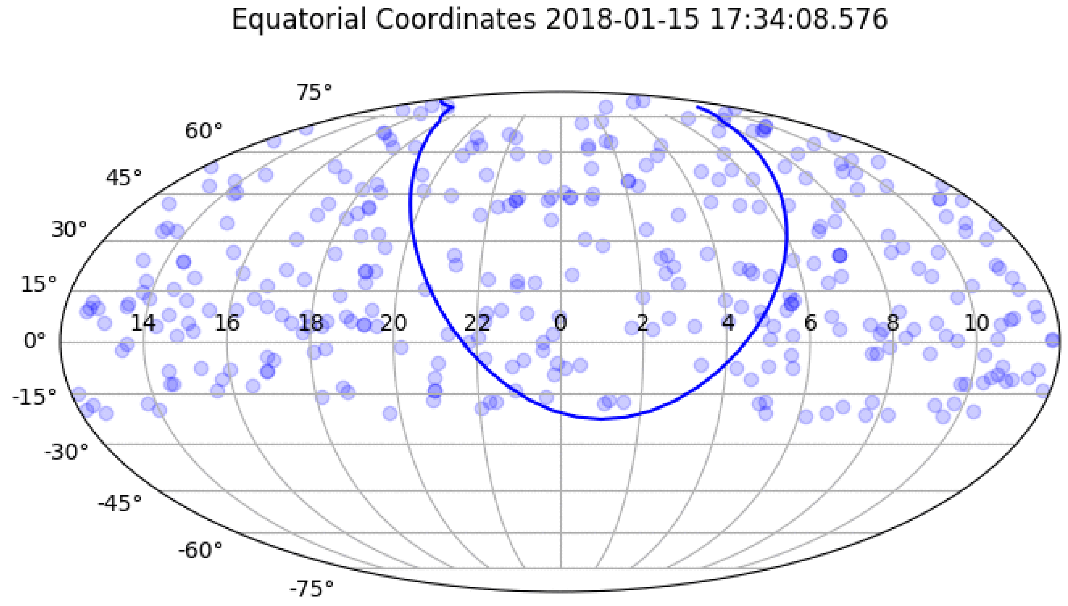



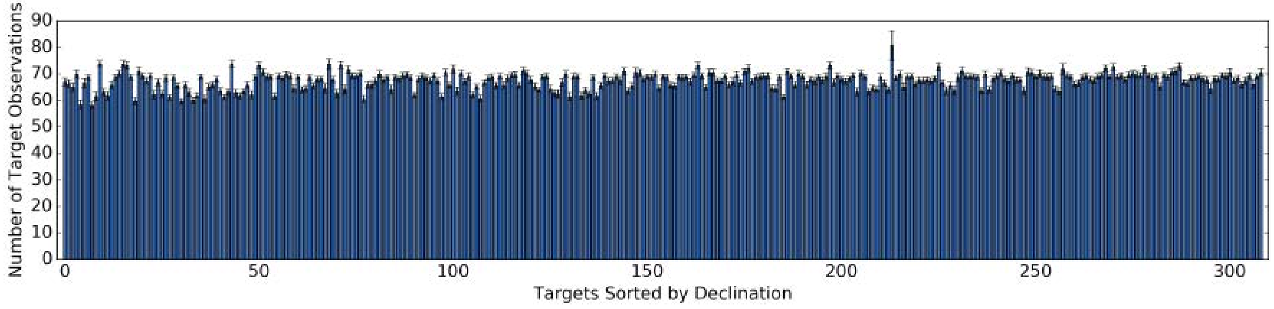
# CARMENES instrument

- Exoplanet research ➔ in operation since 2016
- Trade-off between conflicting soft-constraints
  - Observing Time: maximize the time that the telescope is observing
  - **Observation Deviation:** promote a proper distribution of the observations of the objects to mitigate the problem of scheduling the objects that require longer observations
  - **Observation duration based on S/N**, but fast short-term scheduling (< 1s)



*A. Garcia-Piquer et al., "Efficient scheduling of astronomical observations Application to the CARMENES radial-velocity survey", Astronomy & Astrophysics, 604(A87), 2017*

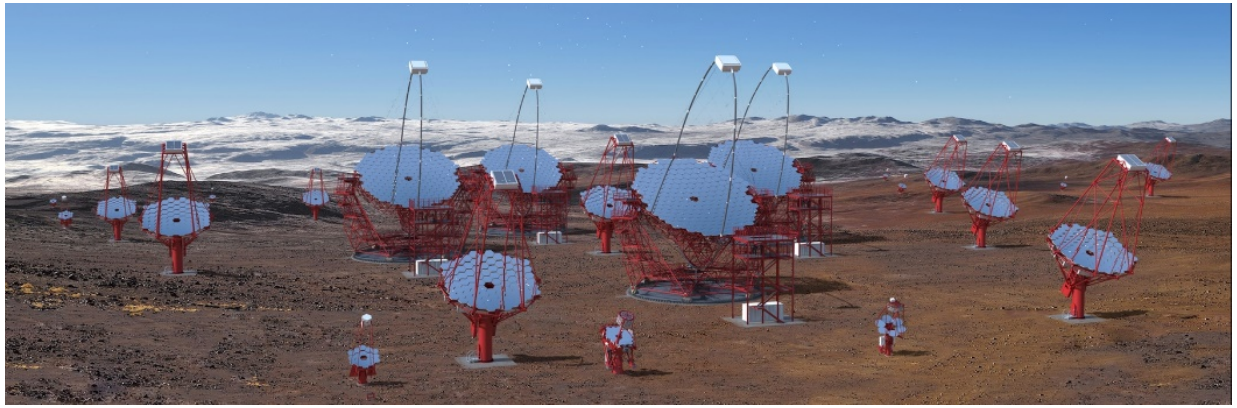



| STARS parameters (50 random trials) | |
|---|---|
| Days planned | 1096 |
| Total targets | 309 |
| Total observable time | 10703.05 h |
| Unfavorable weather time | 4300.23 h |
| Available time for observations | 59.82 ± 0.82% (6402.81 h) |
| Execution time | 23.85 ± 0.11 h |
| **Metrics** | |
| Planned targets | 100 ± 0% |
| Observations done | 20827 ± 293 |
| Working time | 99.05 ± 0.06% (6342.03 h) |
| Tracking time | 84.18 ± 0.03% (5338.77 h) |
| Overhead time | 15.82 ± 0.03% (1003.22 h) |

# Cherenkov Telescope Array

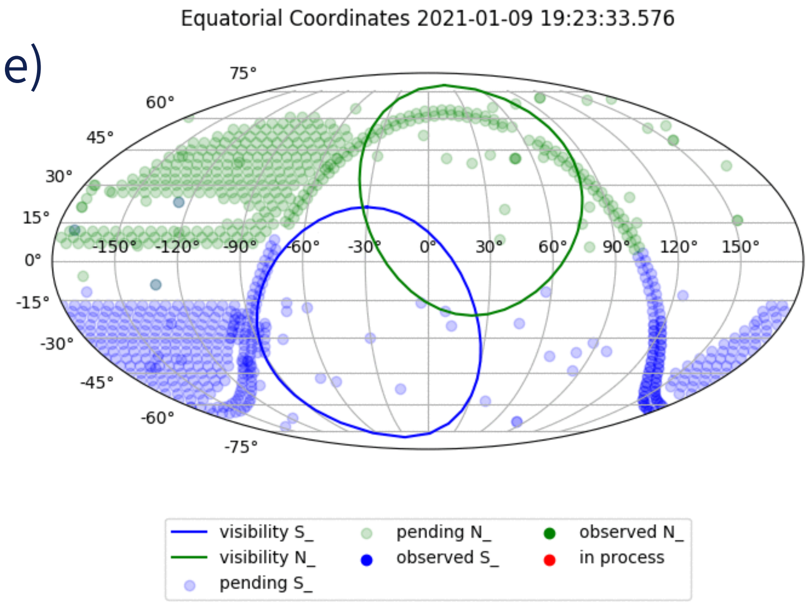
- CTA scheduling conditions
  - Operation tasks
    - Science, calibration, maintenance
  - Observation modes
    - Sub-arrays, compact
    - Convergent/divergent modes
  - Observing time distribution (SB)
  - Two sites (CTAN@ORM / CTAS@Paranal)
    - 20-100 Telescopes/site
    - Independent & coordinated tasks



CTAS&CTAN rendering, Gabriel Pérez Díaz, IAC, SMM

# Cherenkov Telescope Array

- Simulation parameters
  - Target parameters: coordinates, observation time, maximum Zenith Angle, subarray assigned, Moon conditions
  - Observation blocks: duration configured for each target, fixed pointing
  - Real weather conditions based on 2 years monitoring data. Conditions to allow observations are configurable: wind, humidity, cloudless, temperature
  - KSP programmes and surveys in:
    - 1, 3 and 10 years full proprietary time
    - Full array & 3 subarrays (LST, MST, SST) - Configurable!
- Comparison of strategies - 1 yr (WT: slew time + observation time)
    - Observation time metric
      - GA: 3609 observations (1168 hours)
      - MOEA: 4271 observations (1359.68 hours)
    - Slew time metric
      - GA: 8.32% of the WT (104.7 hours)
      - MOEA: 2.62% of the WT (34.26 hours)
    - Execution time: ~ 5 hours to simulate 1 year
- **MOEA allows to complete more objects than GA**



# Cherenkov Telescope Array

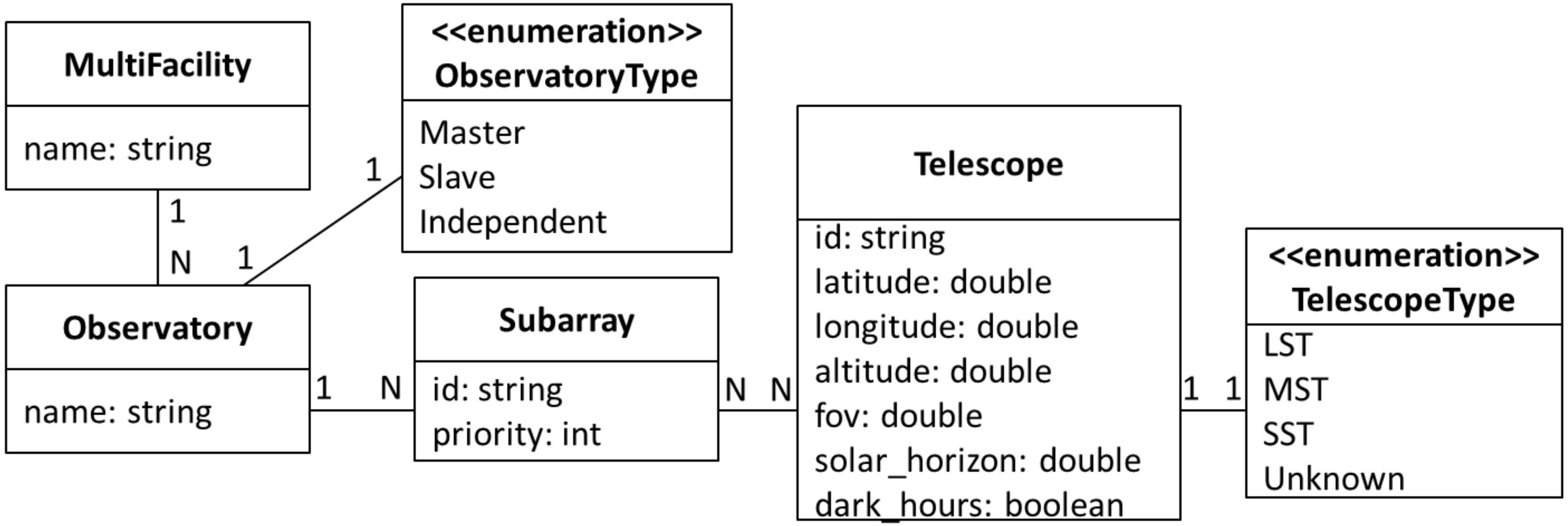
- CTA MOEA – 3 years
- CTA South: 464 targets (3692.11 hours)
- 3 years: 2993.71 hours available (≈1000 hours/year)

| Target Type | #Targets | #Planned (#Completed) |
|---|---|---|
| SURVEY 1 | 170 | 170 (38) |
| SURVEY 2 | 231 | 231 (231) |
| SURVEY 3 | 20 | 20 (20) |
| SURVEY 4 | 5 | 5 (5) |
| SURVEY 5 | 38 | 38 (31) |

| Subarrays | Required Time (h) | #Observations | Working Time (h) | Slew (% of WT) |
|---|---|---|---|---|
| 0 (LST + MST + SST) | 1557.75 | 2012 | 685.76 | 2.20 |
| 1 (LST + MST ) | 200.01 | 697 | 243.80 | 4.70 |
| 2 (MST + SST) | 550.00 | 1653 | 559.65 | 1.55 |
| 3 (LST) | 1384.35 | 2913 | 992.24 | 2.14 |

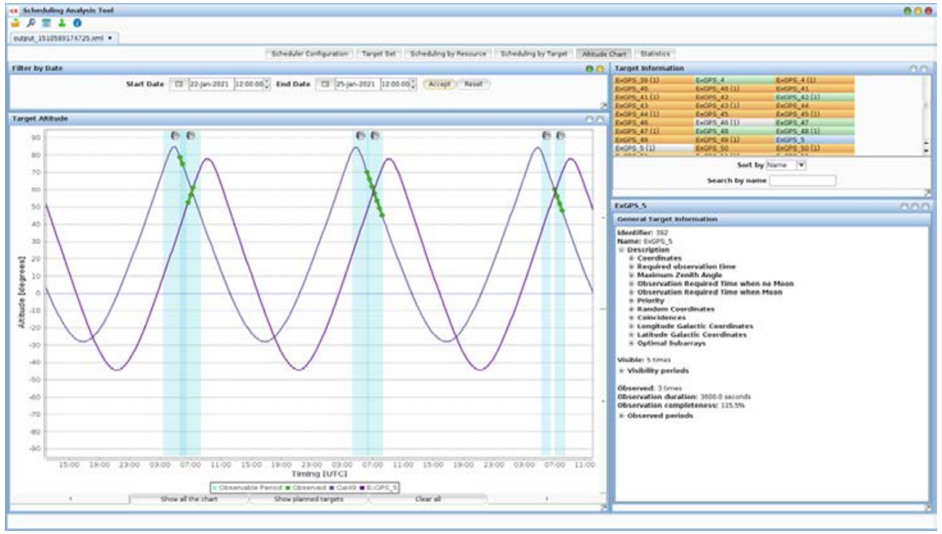
# Multi-observatory coordinated planning

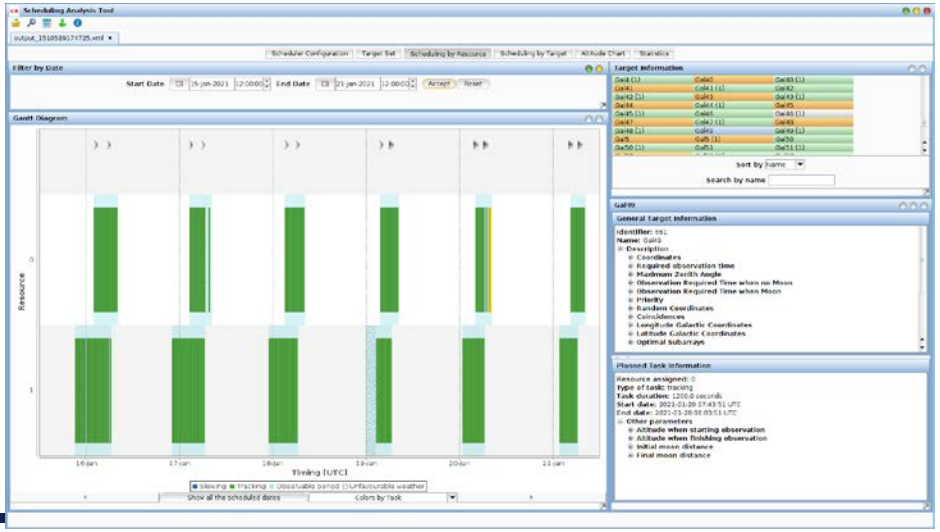
- Science cases: **surveys, steady sources, transient events** (GRBs, GWs, etc.)
- Problem conditions
  - Each observatory contains various subarrays
  - Each observatory has a role: leader, follower or independent
- **Additional Objective → Maximize the simultaneity of observations** (maximize coincident observations or minimize the distance between them)



# Multi-observatory coordinated planning

- Strategies
  - Subsidiary observations: leader - follower
  - Interactive approach: leader - leader
  - Multi-Messenger: random alerts (GW) observed by CTAN&CTAS
- Facilities
  - CTA (CTAN - La Palma, Canary Islands; CTAS – Chile)
  - SKA (Australia, South Africa) → GASKAP (Australia)
  - William Herschell (La Palma, Canary Islands)





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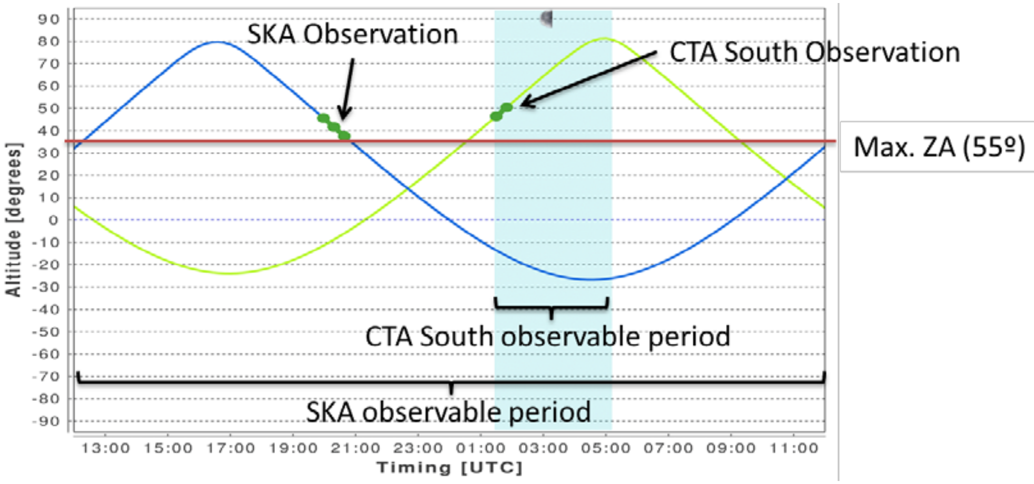
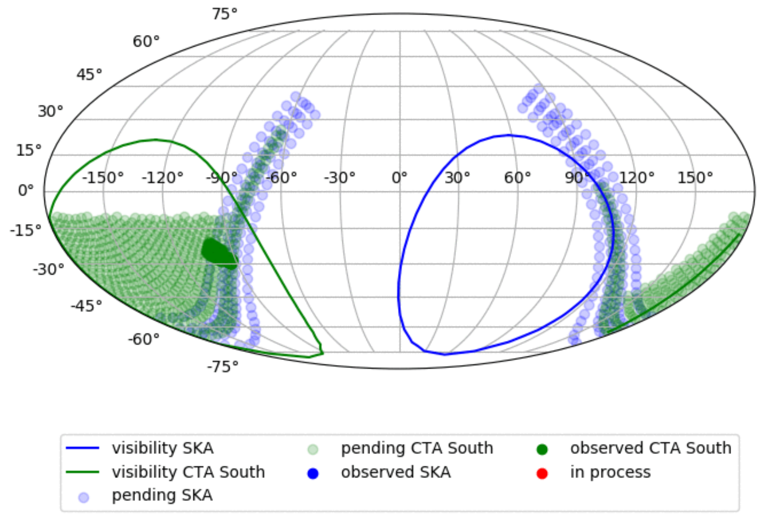
# Multi-observatory coordinated planning

- Simulation configurations ➔ **CTA and SKA coord.**
  - Science test case:
    - CTA: North and South example surveys
    - SKA: GASKAP galactic survey (Dickey, 2013)
  - Scenario (max Zenith: 55°)
    - Leader: site SKA-AU, GASKAP survey
    - Follower: site CTA South, CTA South survey example (FOV: 8 deg ∅)
  - Leader and follower
    - Strategy 1: leader and follower subarrays are optimized simultaneously
    - Strategy 2: leader is optimized individually ➔ Followers do a follow-up



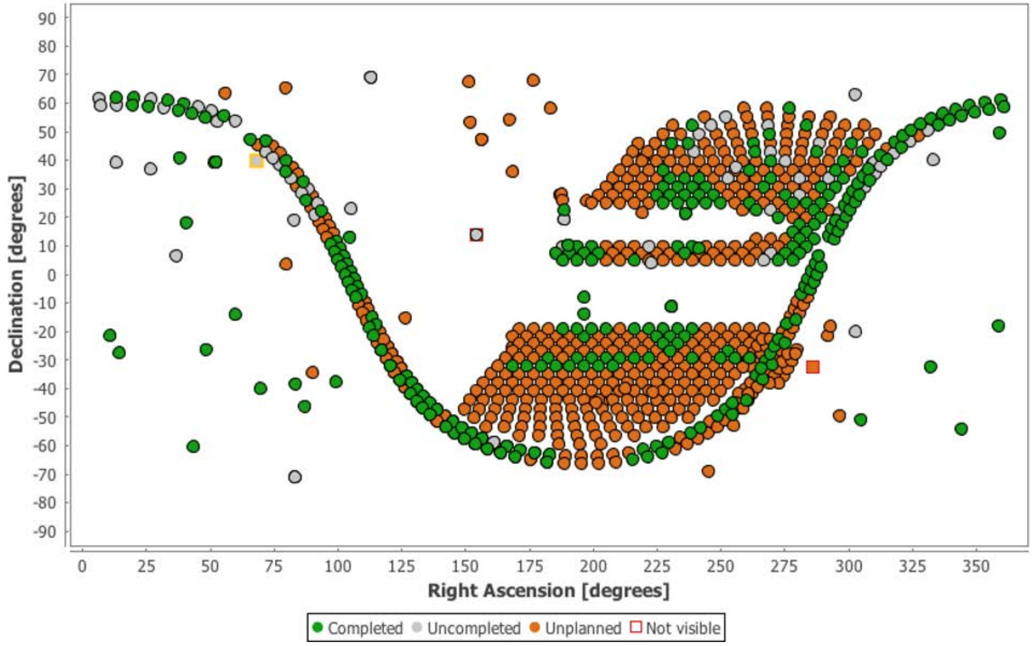
# Multi-observatory coordinated planning

- Simulation results: No targets can be observed simultaneously in CTA South and SKA because of the maximum ZA (55º) ➔ **Optimization reduces time between observations**

| | MO Strategy 1 | | Individually | |
|---|---|---|---|---|
| | SKA | CTA South | SKA | CTA South |
| Required Time (h) | 13300 | 2062.25 | 13300 | 2062.25 |
| Targets in the survey | 275 | 1356 | 275 | 1356 |
| Available Time (h) | 6132 | 1149.78 | 6359.34 | 1193.52 |
| Observing Time (h) | 3968.67 | 713.33 | 3984.67 | 720.67 |
| Slew Time (h) | 255.64 | 72.02 | 88.75 | 27.3 |
| #Observations | 11906 | 2140 | 11954 | 2162 |
| Targets observed (#Planned (#Completed)) | 235 (19) | 652 (212) | 236 (43) | 483 (373) |
| Survey completion (%) | 29.84 | 34.59 | 29.96 | 34.95 |

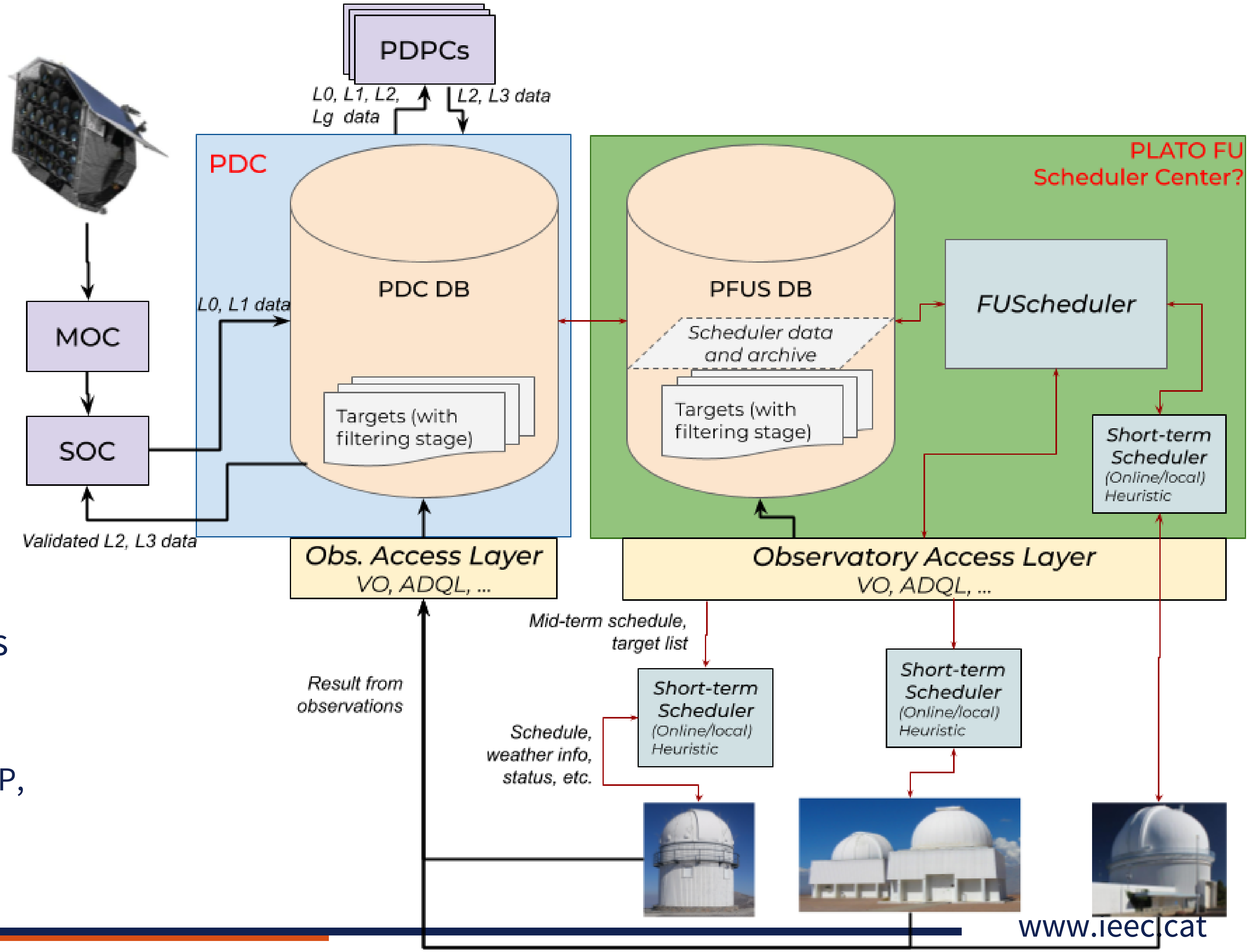
# Multi-observatory coordinated planning

- Simulation scenario ➔ **CTAN&S coordinated & GW transients follow-up**
  - Configuration: 854 targets, required time 7200 h (incl. 2000 h for transients), 2500 h/yr of available time
  - 10 yr simulation (figure: results after 1st yr)



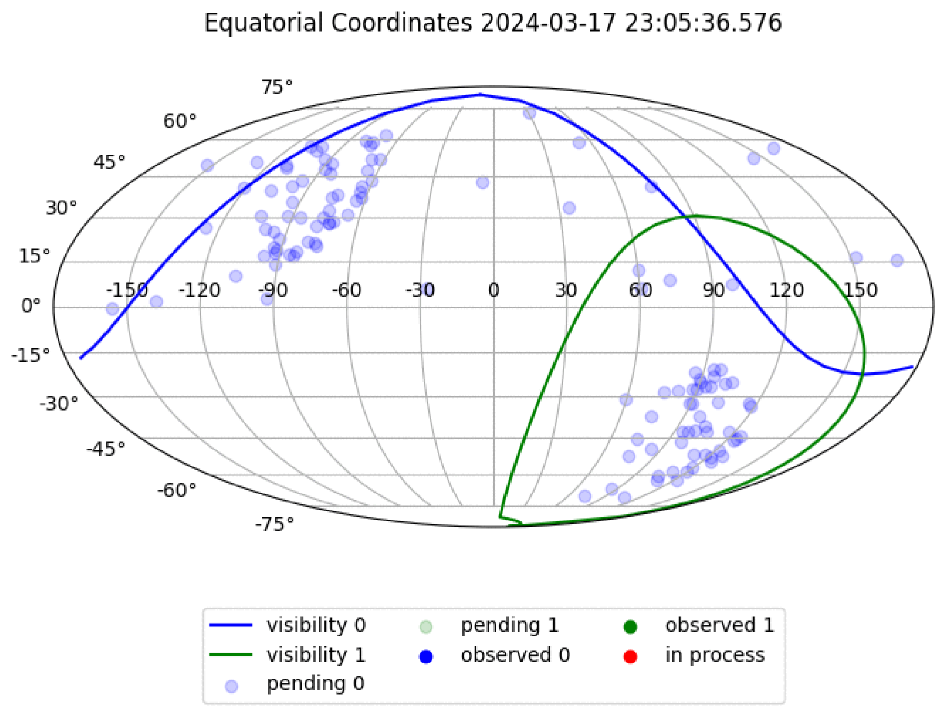
# Multi-observatory – ESA-PLATO FU Scheduler

- Overall architecture & requirements
- Interfaces and protocols
  - From Telescopes (visibility, availability, observing constraints)
  - Task submission to Telescopes
  - Task status from Telescopes to scheduler archive
  - Reactive or pro-active communication
  - Protocols: VO visibility & observing constraints, VOEvents, heterogeneous protocols
- Optimization metrics
- Identify existing tools, approaches or best practices that may be reused
  - E.g.: Las Cumbres Observatory (TOM), ESA VO protocols (ObjVisSAP, ObjLocTAP), TFOP, Gaia Alerts, LIGO/Virgo EM follow-up…



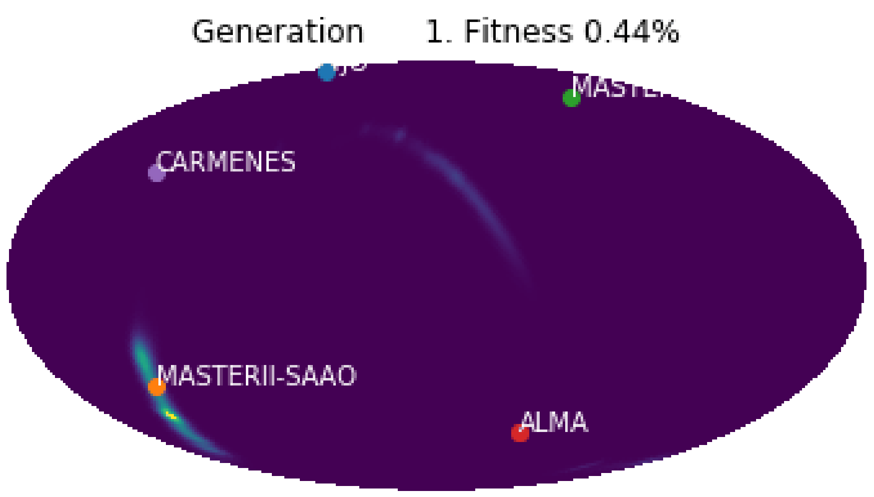
# Multi-observatory – ESA-PLATO FU Scheduler

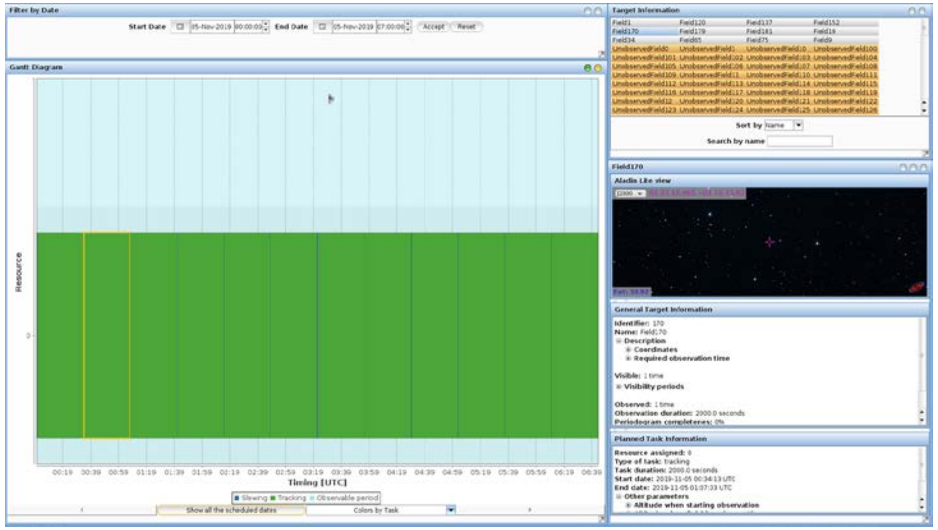
- Simulations using 100 Gaia DR2 sources randomly picked up from PLATO N+S fields
- Scheduler executed using CARMENES configuration, simulating:
  - March+April 2024
  - Locations: CARMENES (CAHA) & HARPS (La Silla)
  - Bad weather
  - Only ≥40º targets
  - Exposure time fixed to 15min
  - Telluric standards used in CARMENES



# Multi-observatory – GW Follow-Up Scheduler

- Goals: Optimize the GW follow-up via a multi-telescope scheduler
- Status: Fully functional prototype
- Two-step procedure
  - First step: Input LIGO/Virgo alert, generate list of best fields for each telescope
  - Second step: Input available time for a telescope, output schedule



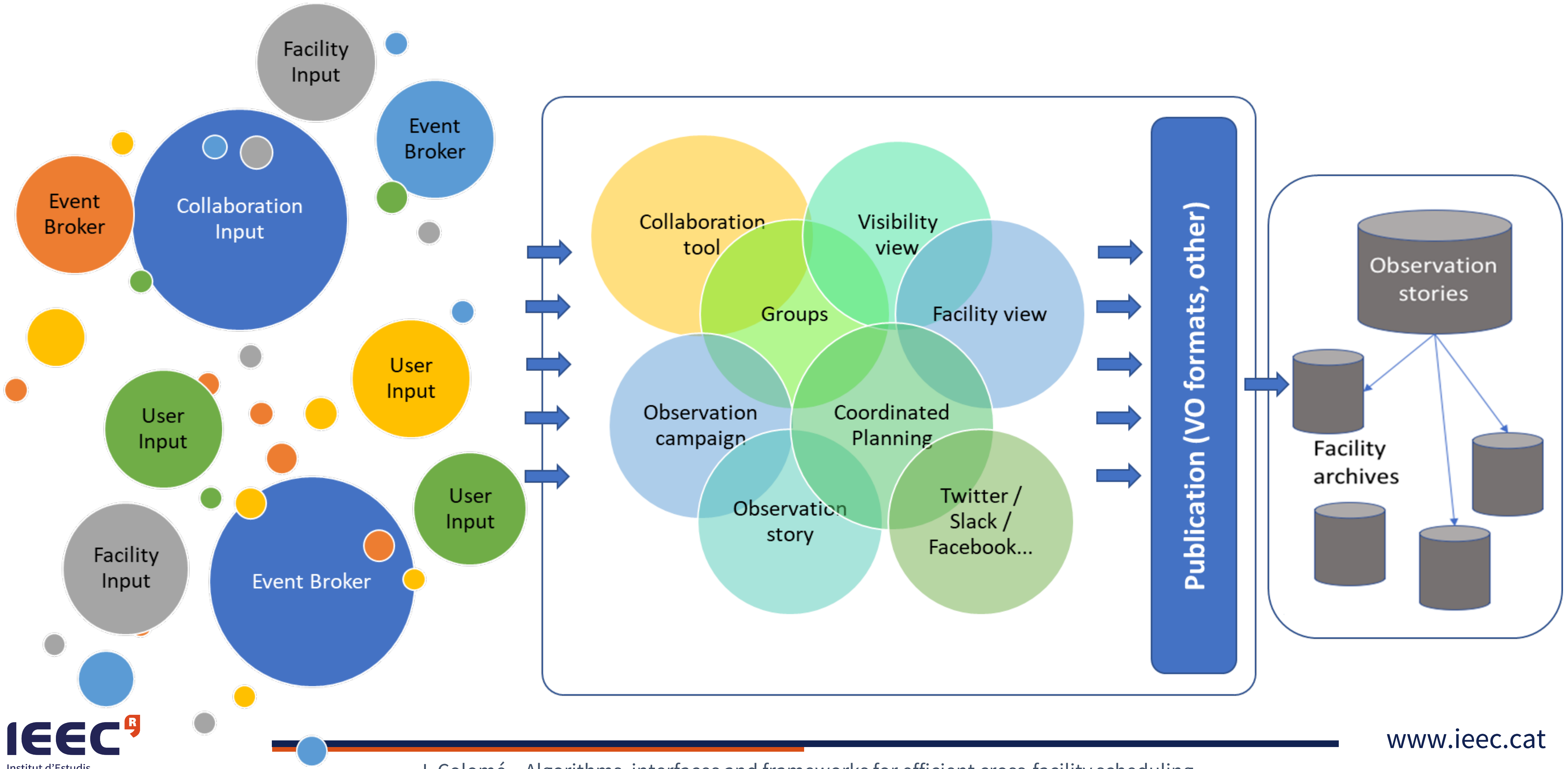
# Multi-Messenger coordination Platform

- **Platform to facilitate collaborative, follow-up observing by joining together and adding to available tools**
- Recent increase in collaboration in multi-messenger astrophysics, both for planned observations and in response to transients
  - Transient phenomena are the next ‘big thing’
  - Gravitational waves → LSST and SKA → millions of raw events per night!
  - All could require follow-up – how do we do this efficiently?
- **ASTERICS**: a network of facilities and organizations involved in multi-messenger astrophysics

- Initiative Proliferation
  - Target Filtering - event brokers add value to the event stream
  - Collaboration - skills, access to instruments, manpower
  - Observation scheduling – multi-instrument coordination, editing
  - Context building – harvest archive data, correlate alerts
  - Tools - Aladin Lite, LCO TOM toolkit
  - Interface definition
  - Umbrella projects

SCiMMA

# Multi-Messenger coordination Platform

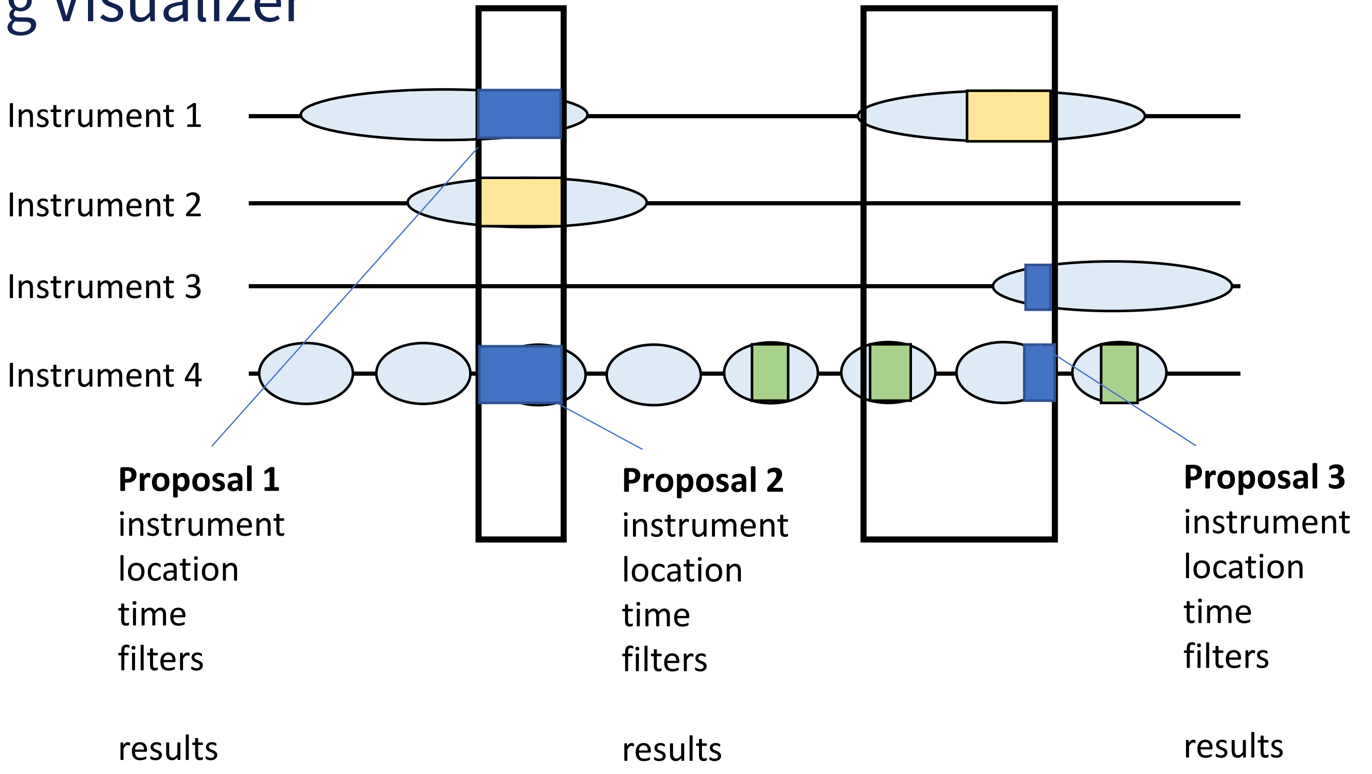


# Multi-Messenger coordination Platform

- Pilot Scheduling Visualizer

Query object visibility services to find out what location is visible for each instrument

Query observation locator services to find out which instruments are planning to observe that location in the future

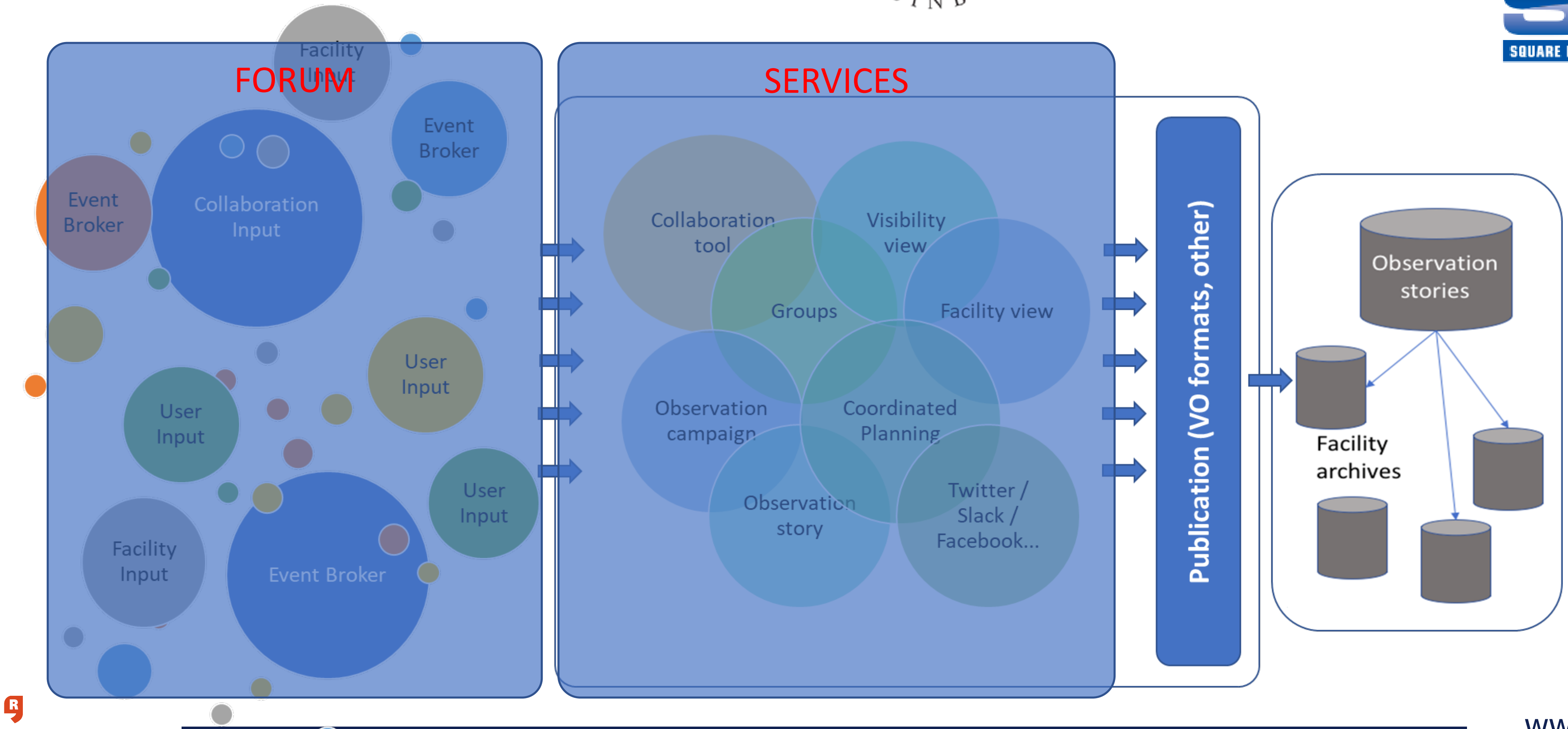



The system will plan and track new observation proposals for the target objects

Combine historical information about the location with visibility and future plans for observations

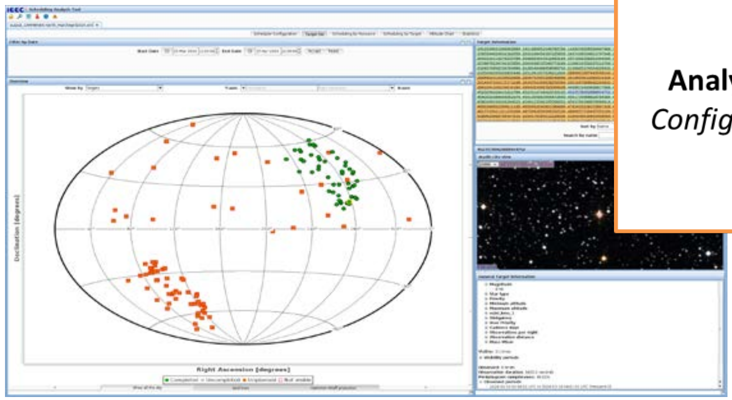
Coordinate the best times to request new follow-up observations

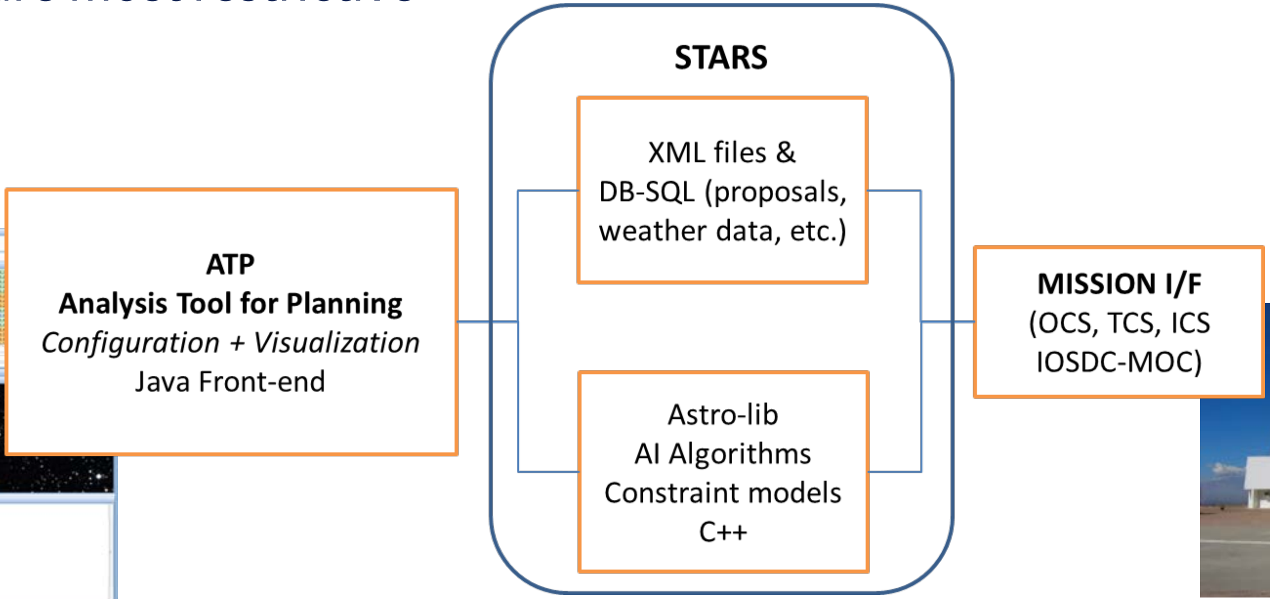
# Multi-Messenger coordination Platform



# Conclusions

- STARS is a framework for **observatory time scheduling**
  - Algorithms used are: GA, MOEA and astronomical heuristics. Other global search algorithms can be applied following the same steps
  - Hard and soft constraints can be adapted and generalized to different cases
  - Tool to estimate the efficiency of the survey, and to study the impact of different parameters or which targets are most restrictive

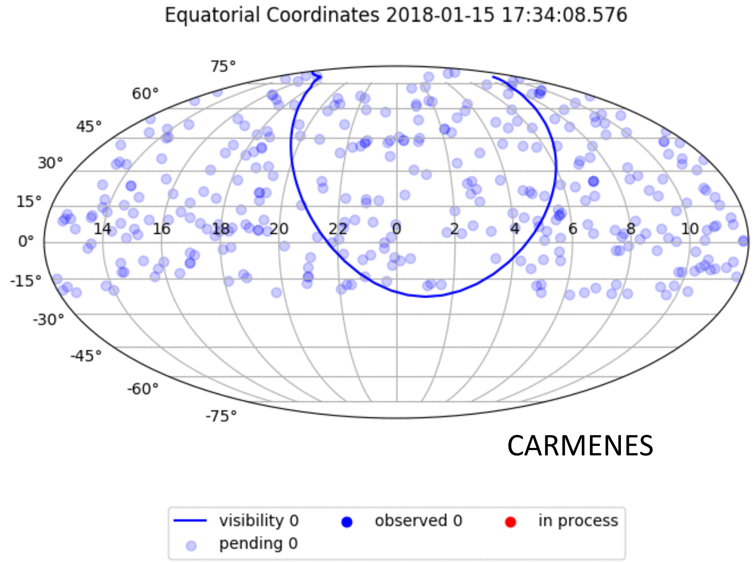




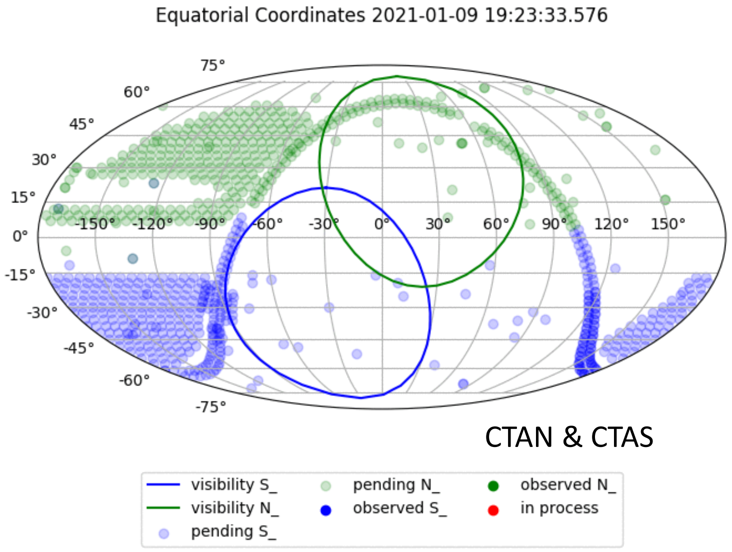

# Conclusions

- STARS is applied to different projects:
  - In operation: CARMENES & TJO
  - Under construction (simulation mode): ARIEL-ESA, CTA & CTA-SKA
  - Research project (simulation mode): CTA & GASKAP, PLATO

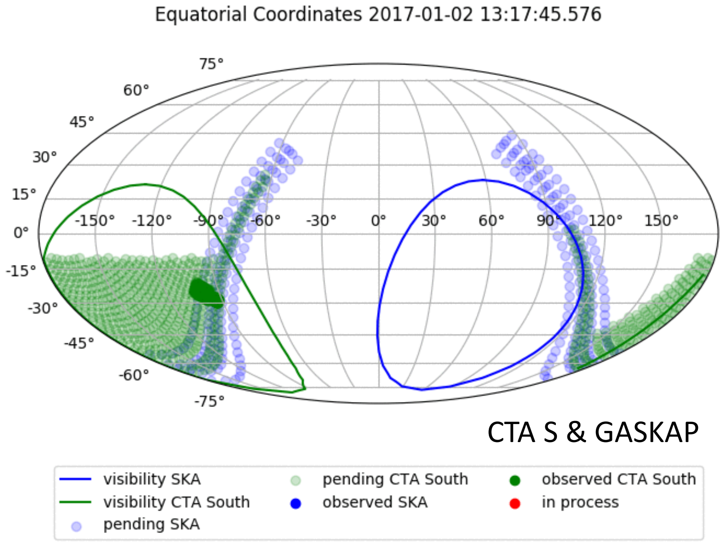
**Real-time service in an operational control architecture**




**Optimization of time-critical events**




**Multi-observatory coordinated observations & MM science**



# Algorithms, interfaces and frameworks for efficient cross-facility scheduling

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**ESA/ESO SCIOPS Workshop 2019**