

Power-Optimal Scheduling of LEO Satellite Networks

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POWER TO THE PEOPLE. VERIFIED.

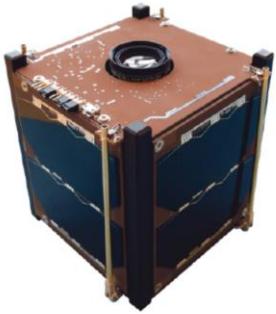
Masses of LEO Satellites



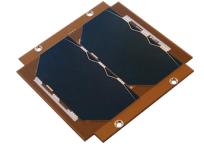
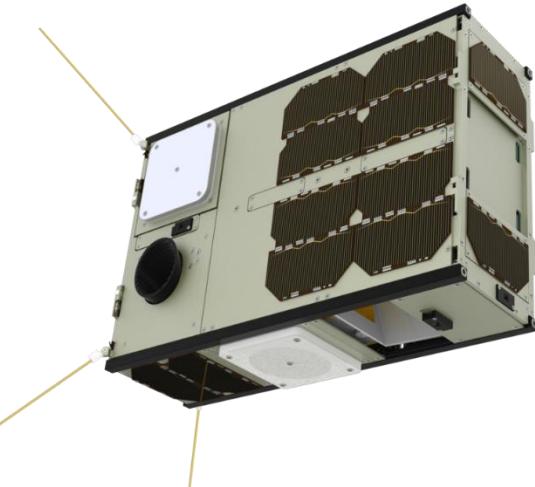
LEO?

- Low Earth Orbit
- Maximum 2000 km above our heads
- Outer rim of Atmoshpere – Thermosphere ... Exosphere
- One rotation needs to last 130 – 80 minutes to counter gravity
- Populated by more than half of all man-made Earth-orbiting objects
- Low distance to Earth favorable for power-efficient and low-latency communication
 - ISS orbits in LEO at about 400 km

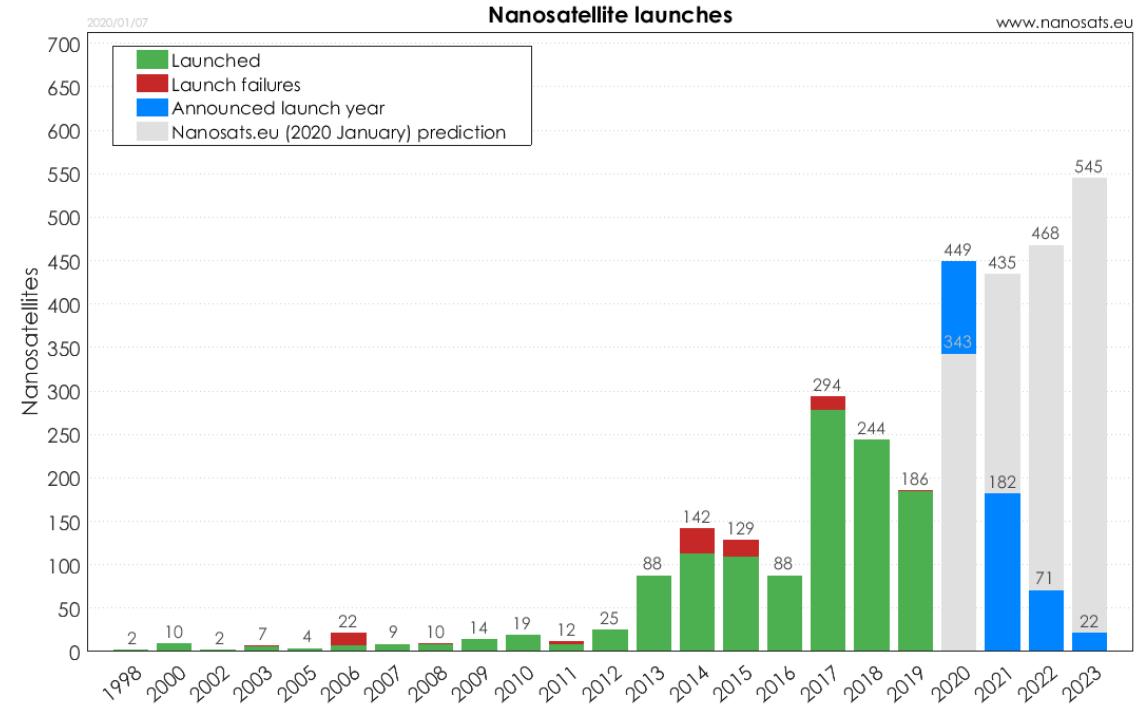
Nano Satellites



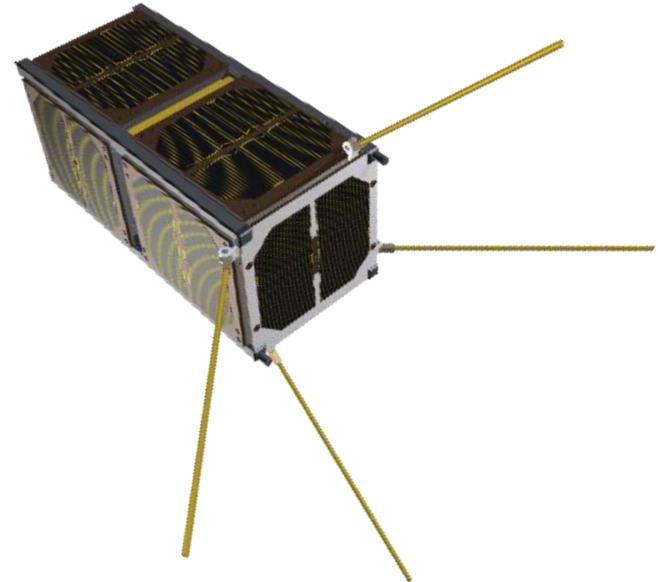
Cubes



- Up to 10 kg
- Multiples of 1 liter cubical units
- Fast and cheap to build – COTS

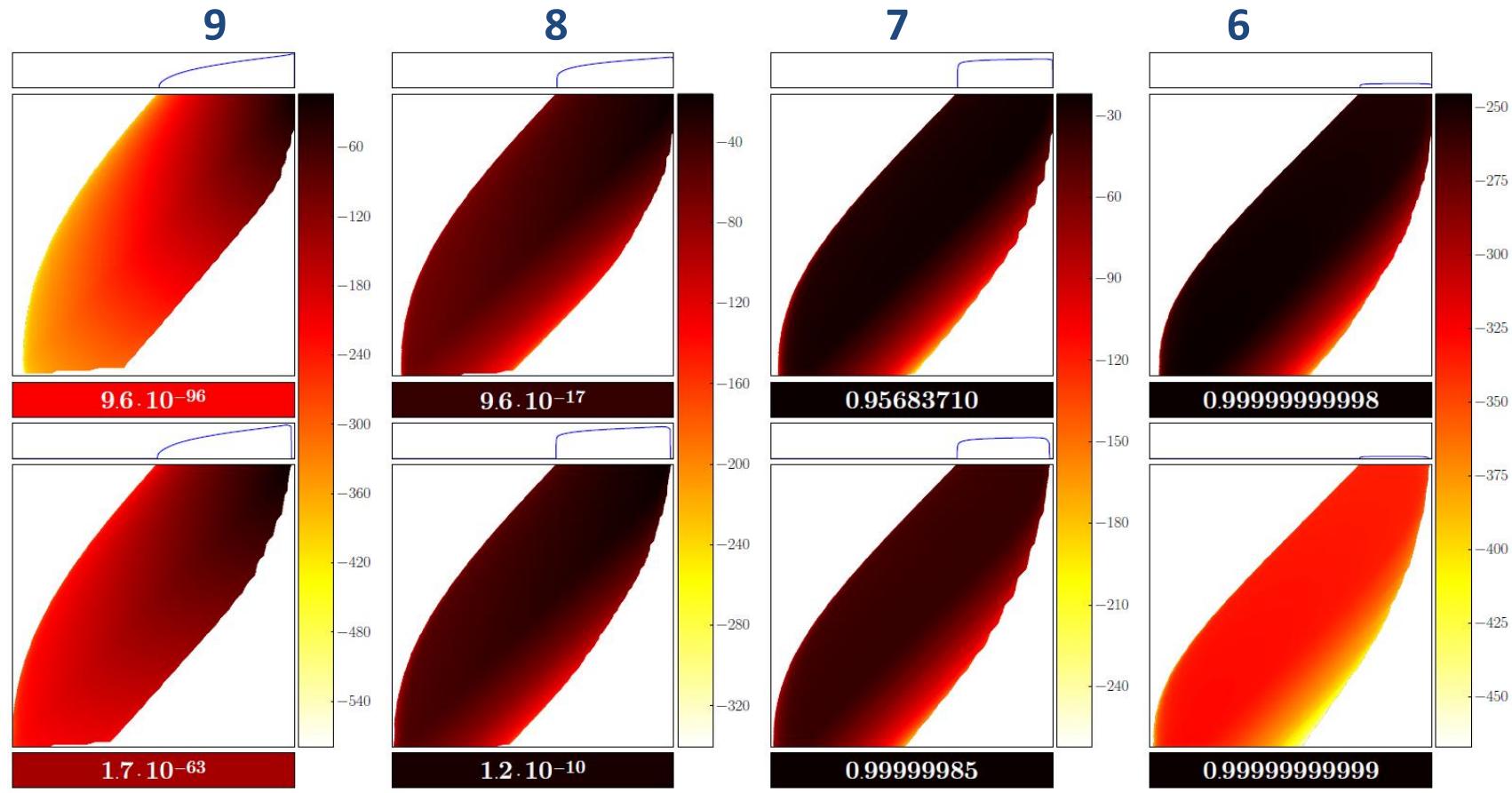


- 2U – 2 liter
- Launched in November 2013
- Payloads:
 - software defined receiver for aircraft signals
 - color camera for earth observation
- Telemetry transmitted on amateur radio frequency
- Massive amounts of data collected
 - battery voltage, temperature, solar infeed, ...
- Is still out there collecting data.



Resilience Analysis for GOMX-1

Number of Solar Panels in Operation



Survival Probability

Time Horizon 1 Year

Probabilistic Load Model

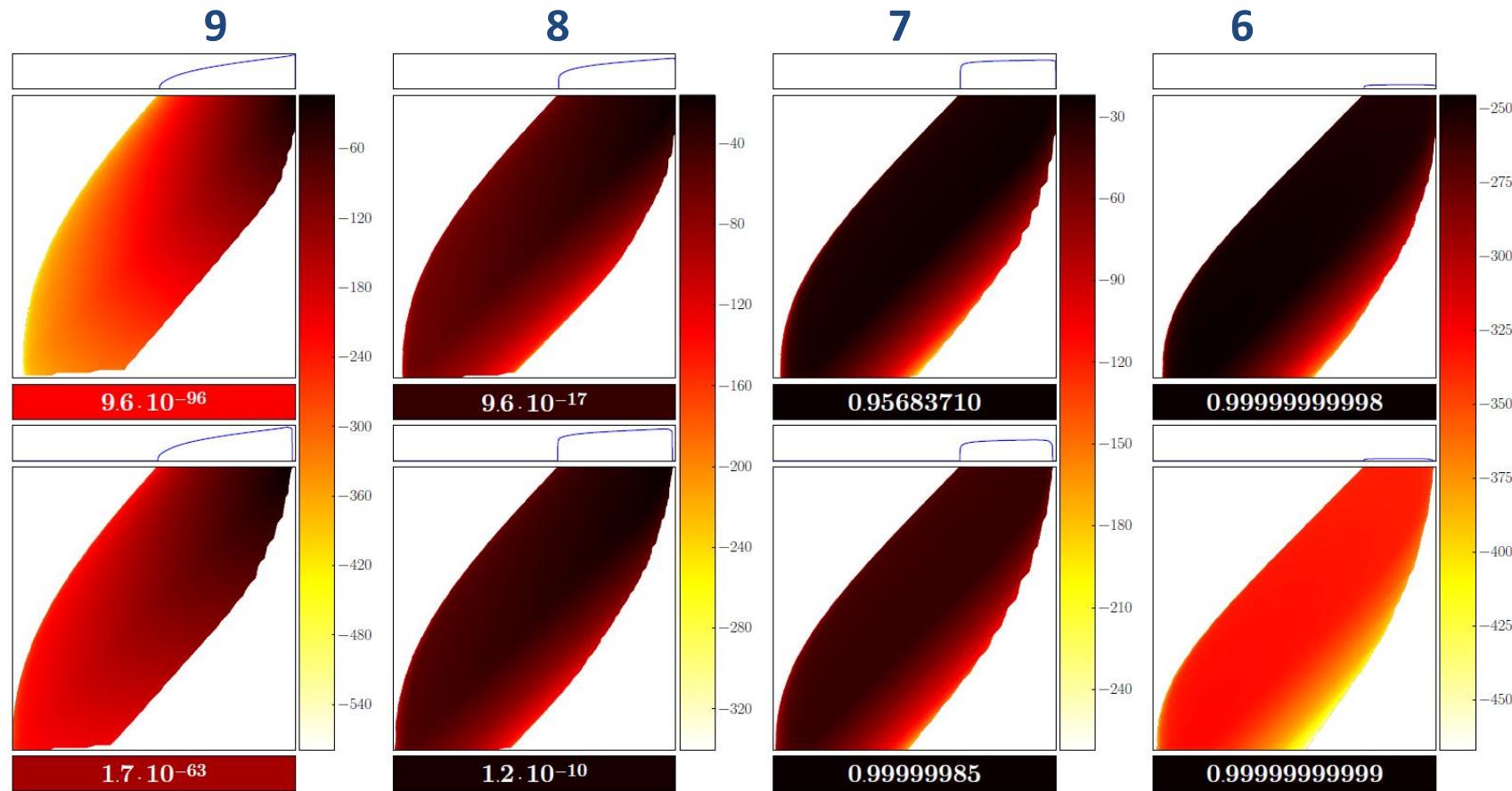
Over-
approximation

Under-
approximation



Under the Hood

Number of Solar Panels in Operation



Survival Probability

Time Horizon 1 Year

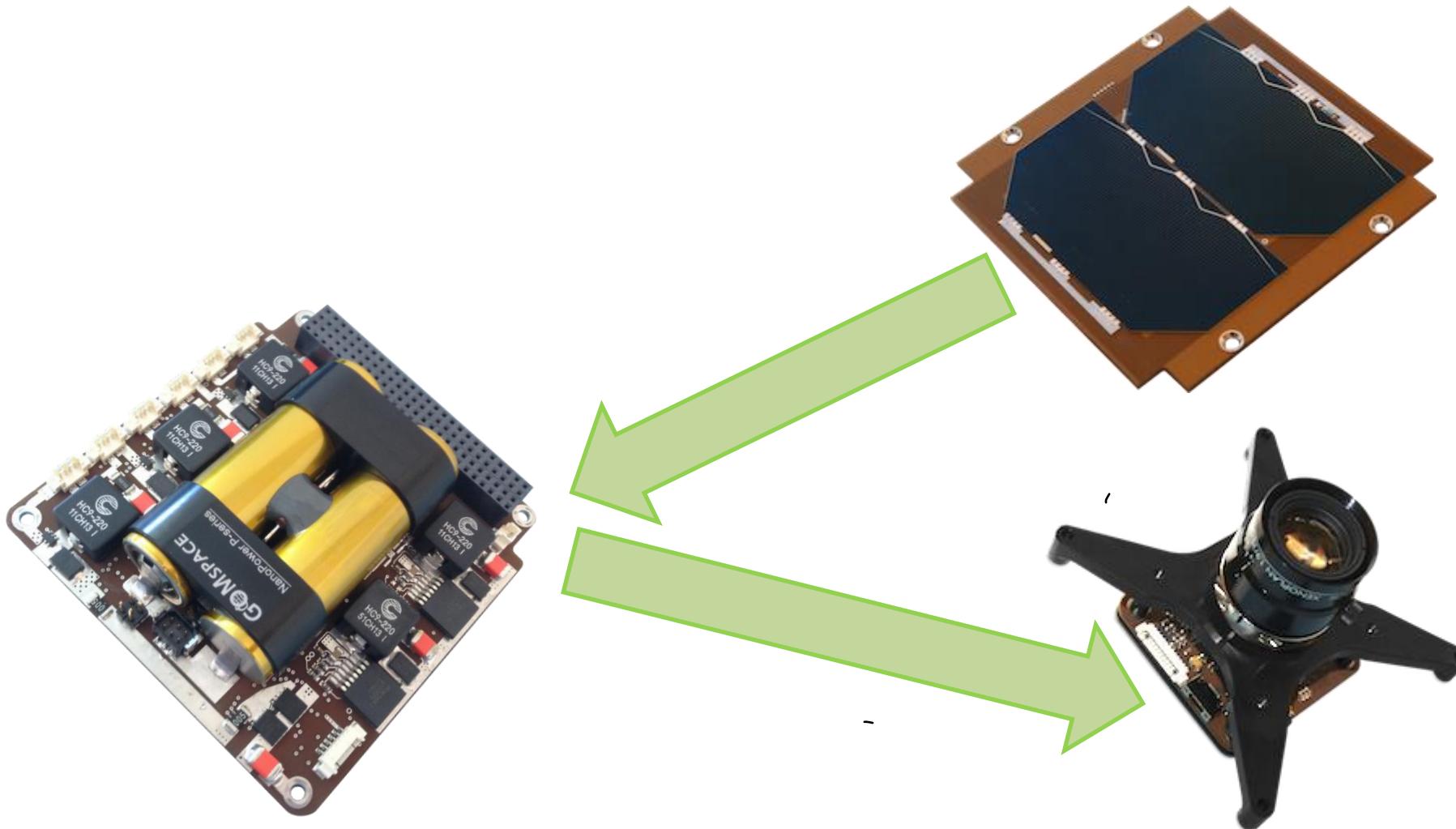
Probabilistic Load Model

Over-
approximation

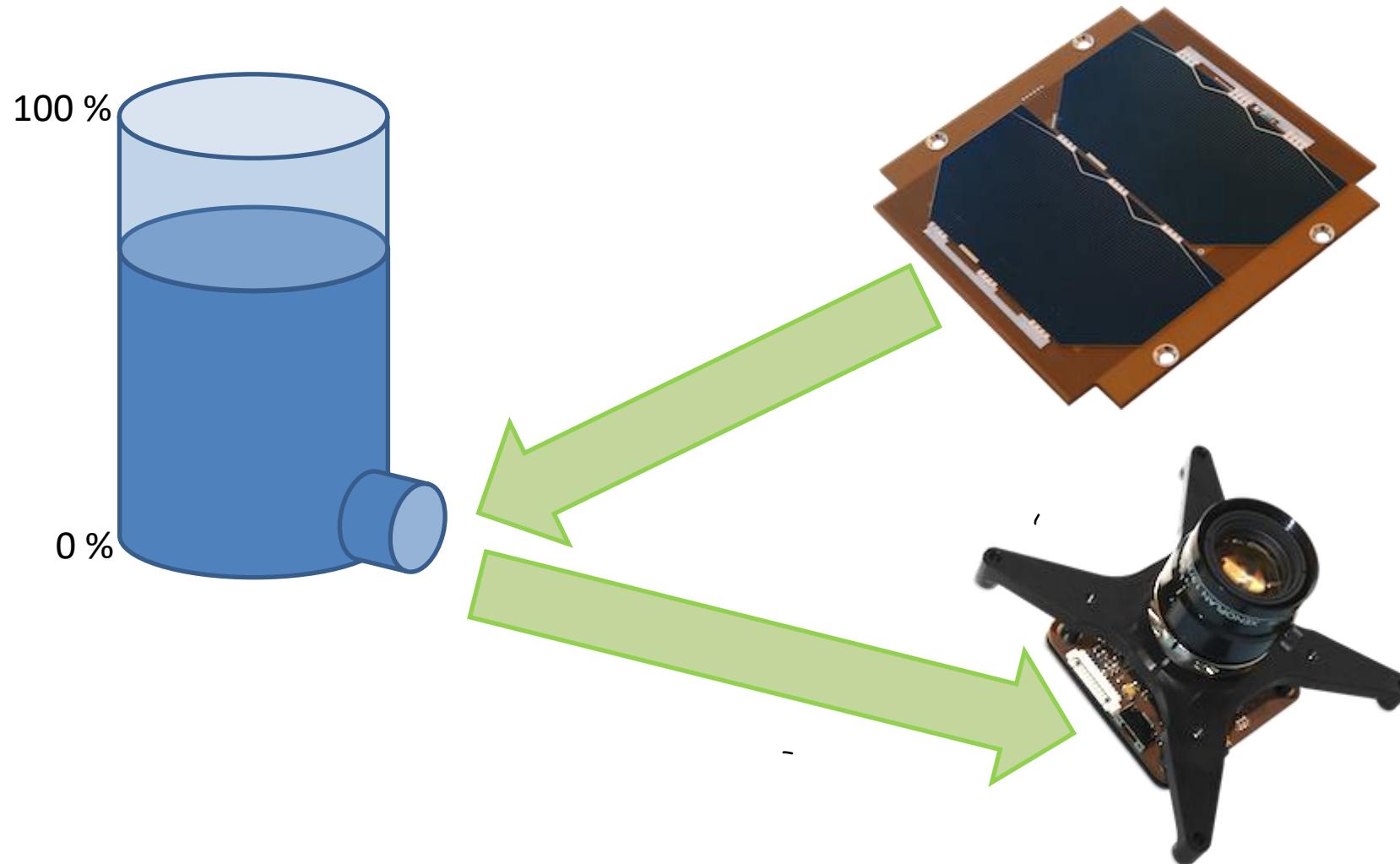
Under-
approximation



Under the Hood ①



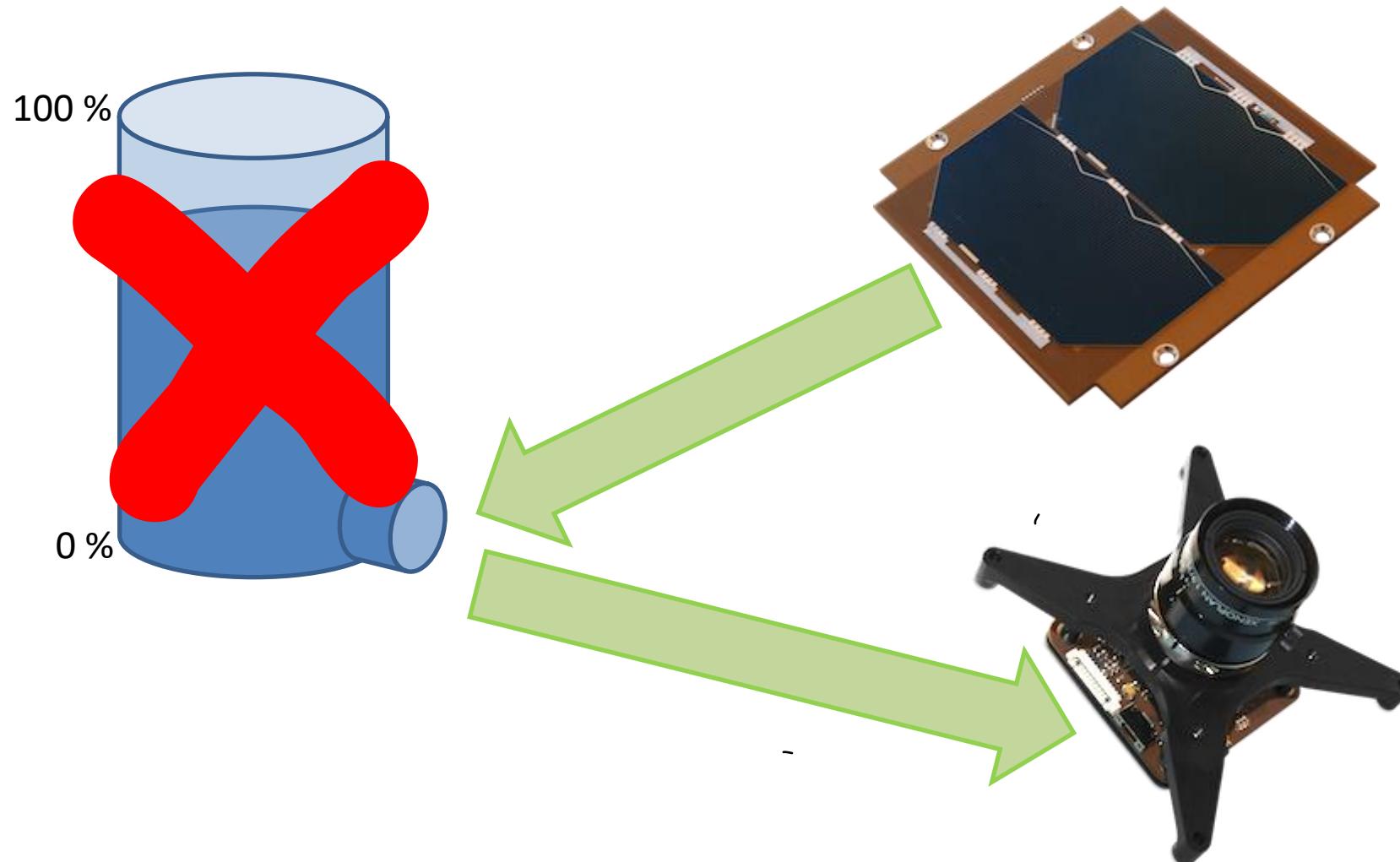
Under the Hood ①



Accurate Battery Model is Crucial



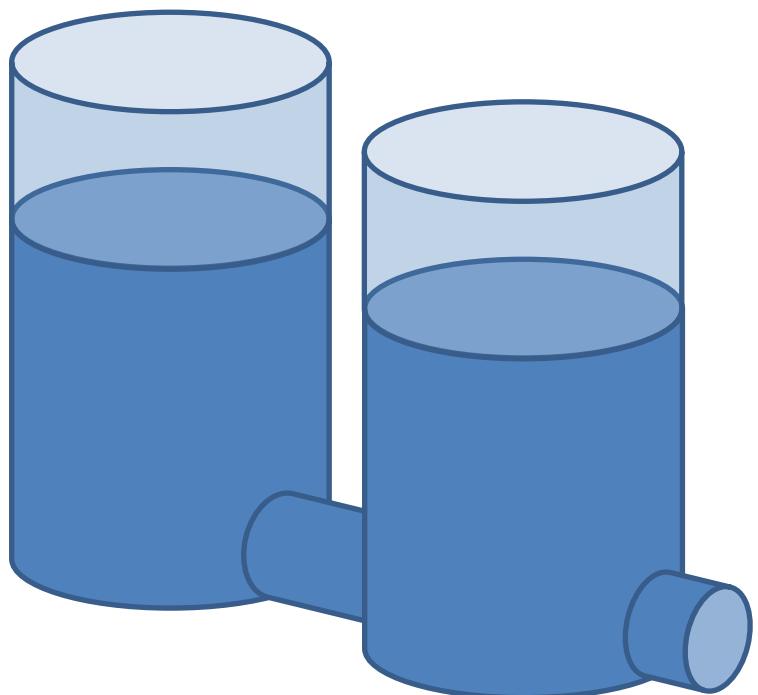
Under the Hood ①



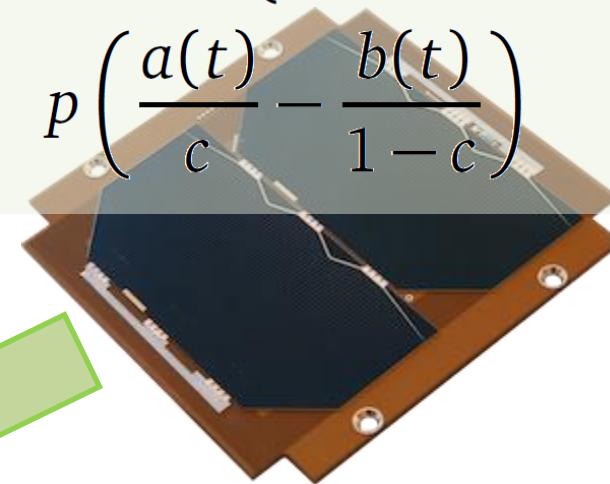
Accurate Battery Model is Crucial



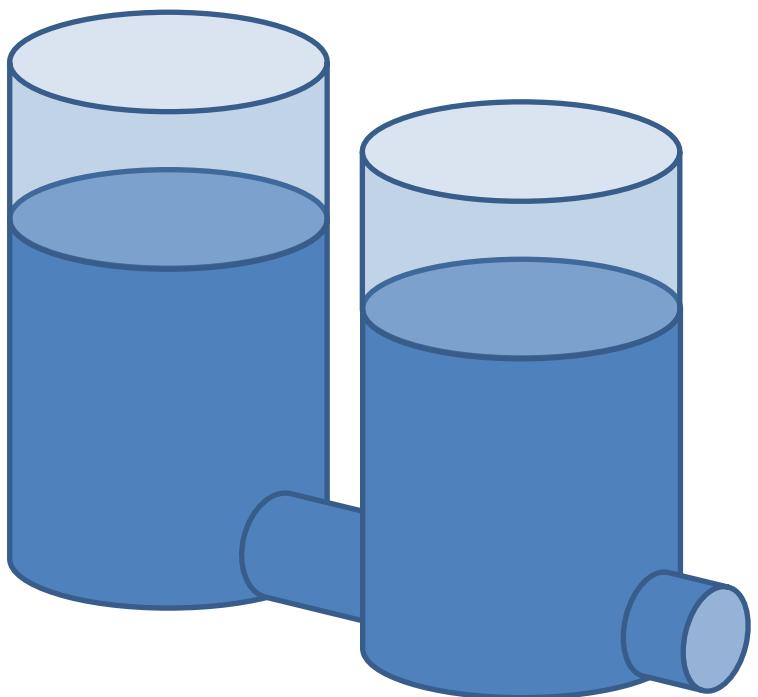
Under the Hood ①



$$\dot{a}(t) = -I + p \left(\frac{b(t)}{1-c} - \frac{a(t)}{c} \right)$$
$$\dot{b}(t) = p \left(\frac{a(t)}{c} - \frac{b(t)}{1-c} \right)$$



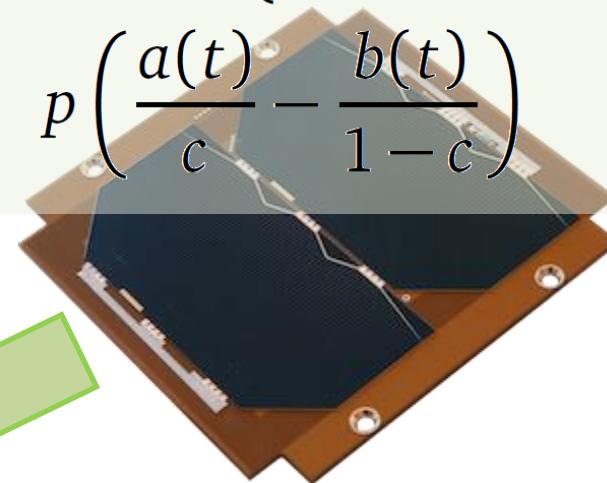
Under the Hood ①



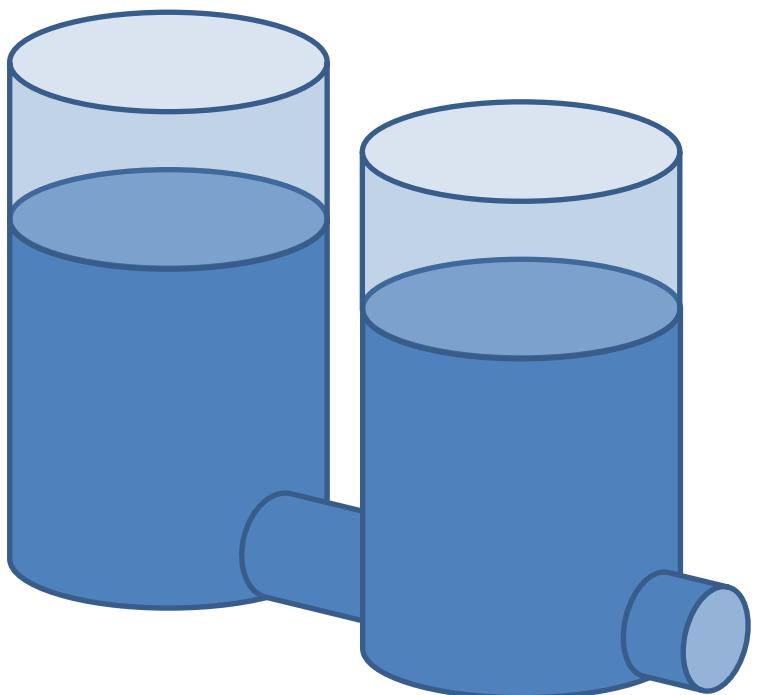
Can capture
+ Spatial imbalance of ion density

$$\dot{a}(t) = -I + p \left(\frac{b(t)}{1-c} - \frac{a(t)}{c} \right)$$

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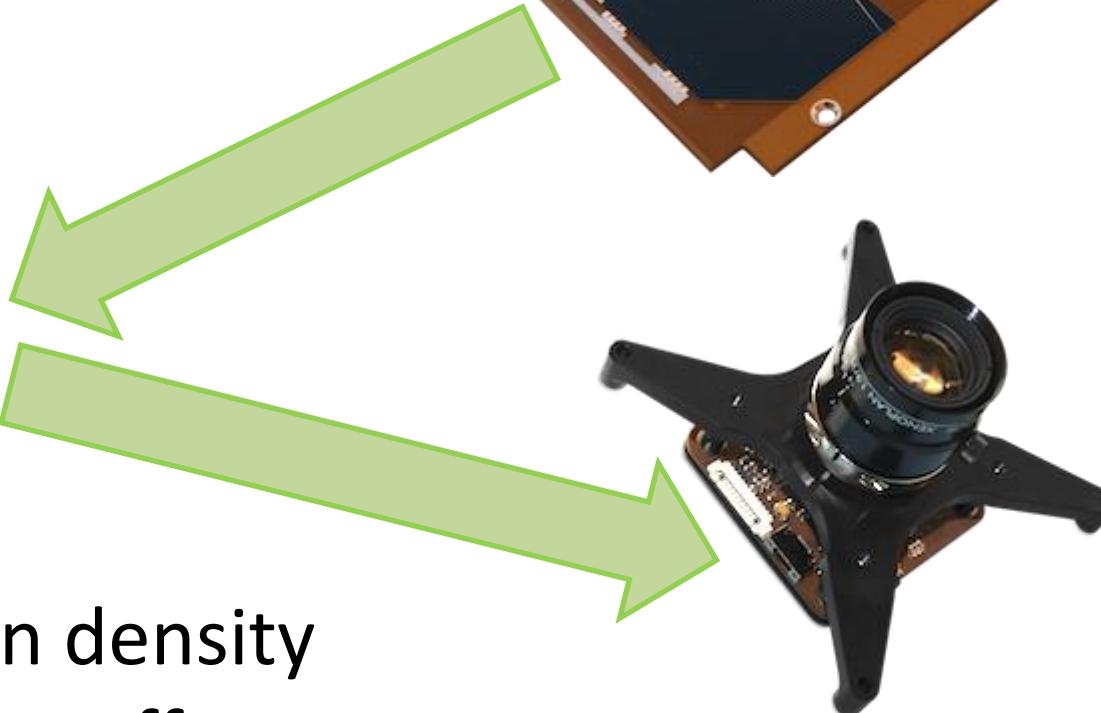
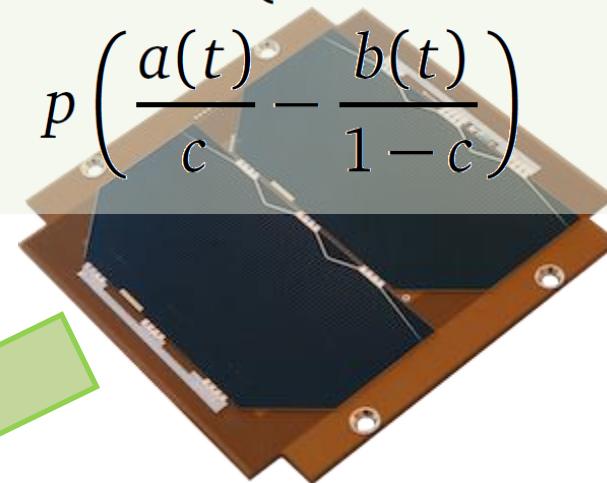


Under the Hood ①



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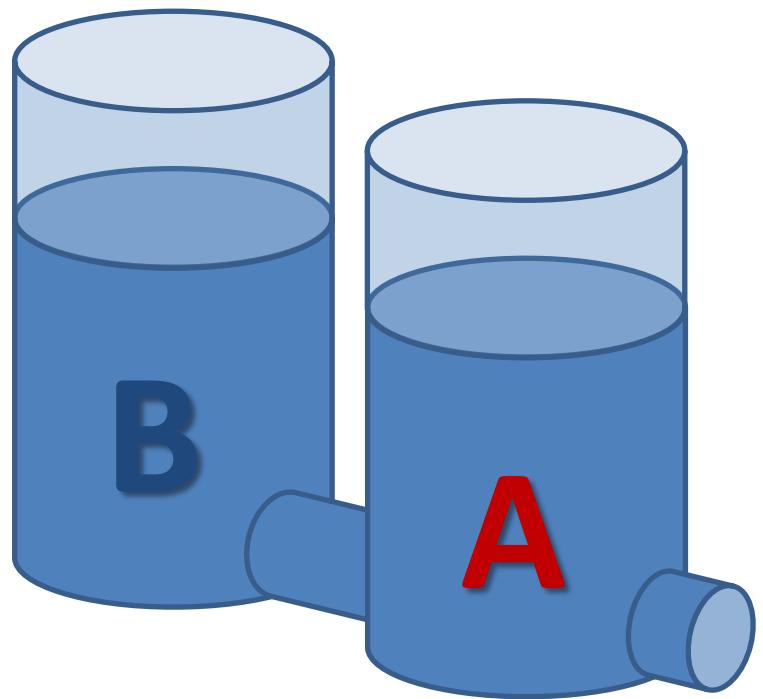


Can capture

- + Spatial imbalance of ion density
- + Rate-capacity effect
- + Recovery effect



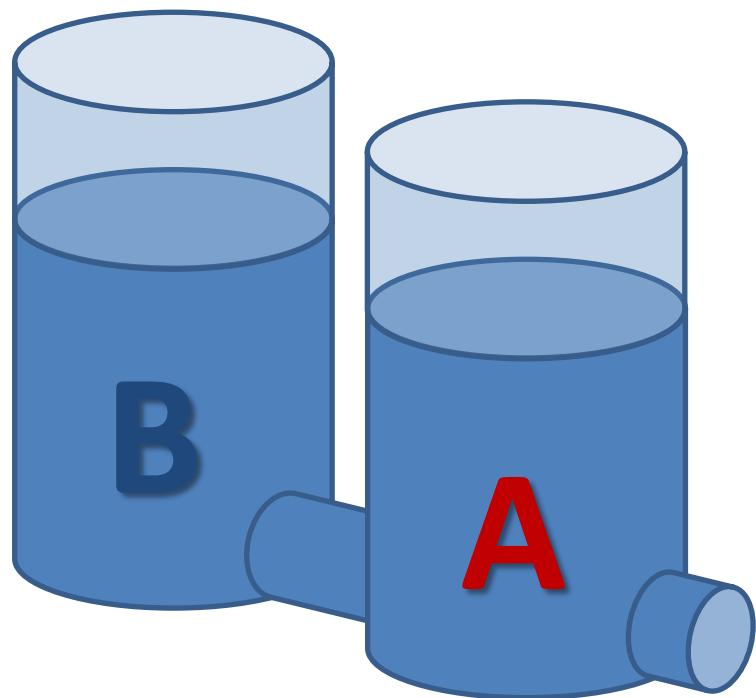
Under the Hood ①



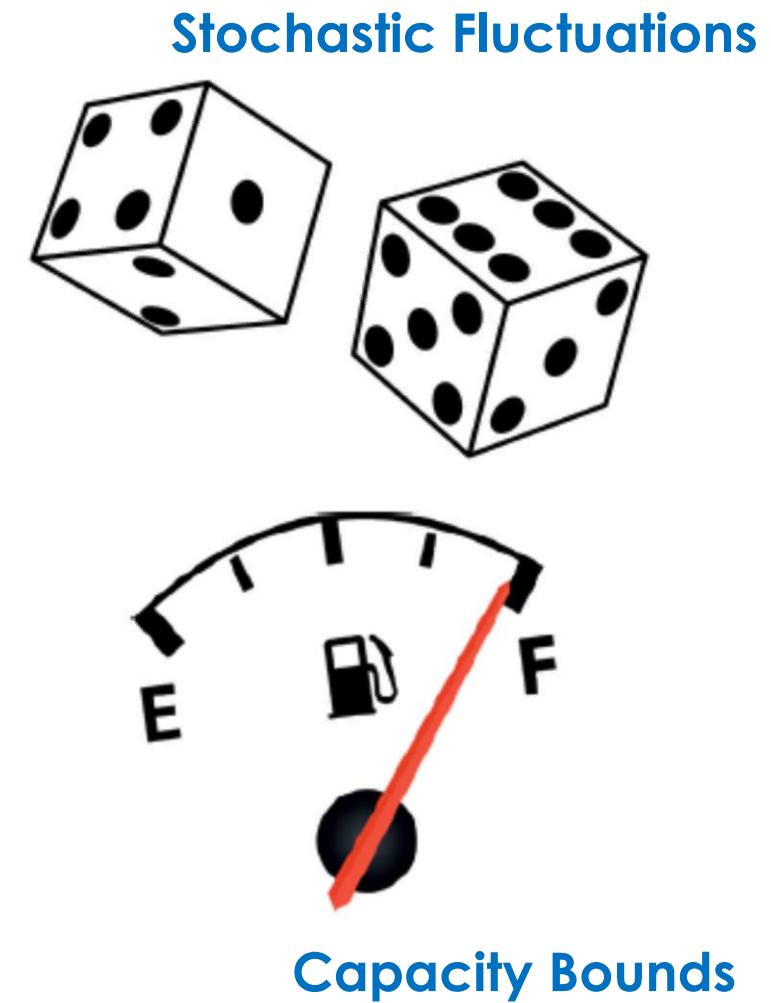
“Kinetic Battery Model”



Under the Hood ①



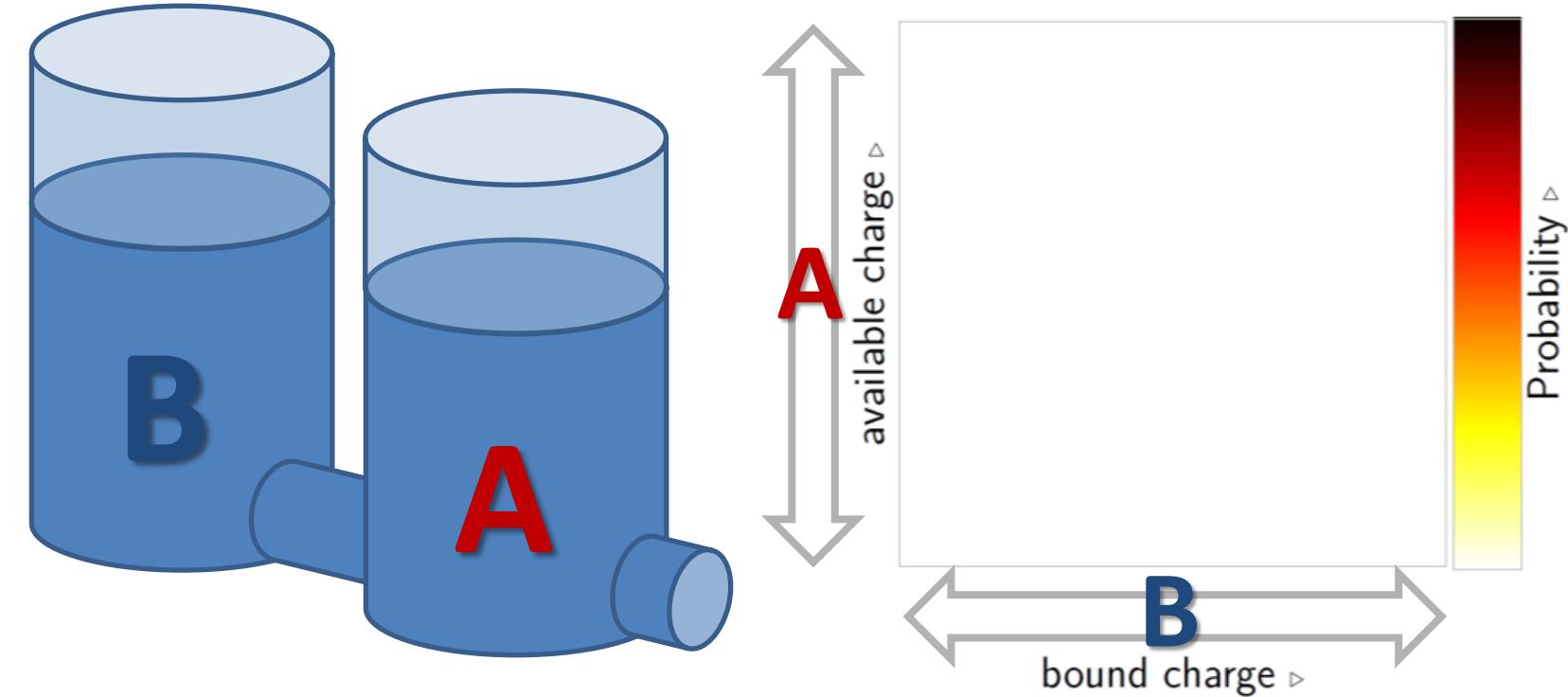
+



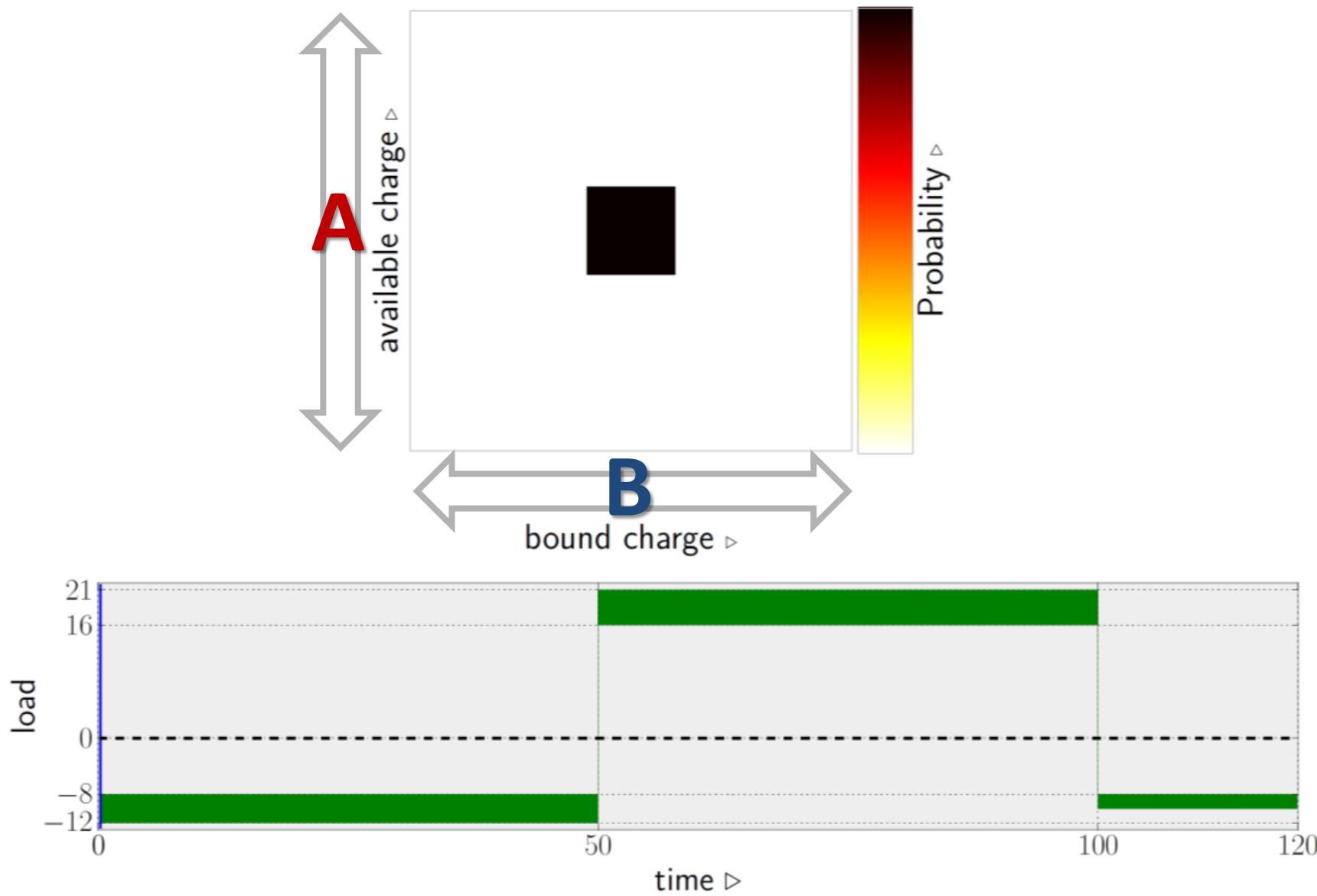
“Kinetic Battery Model” enhanced



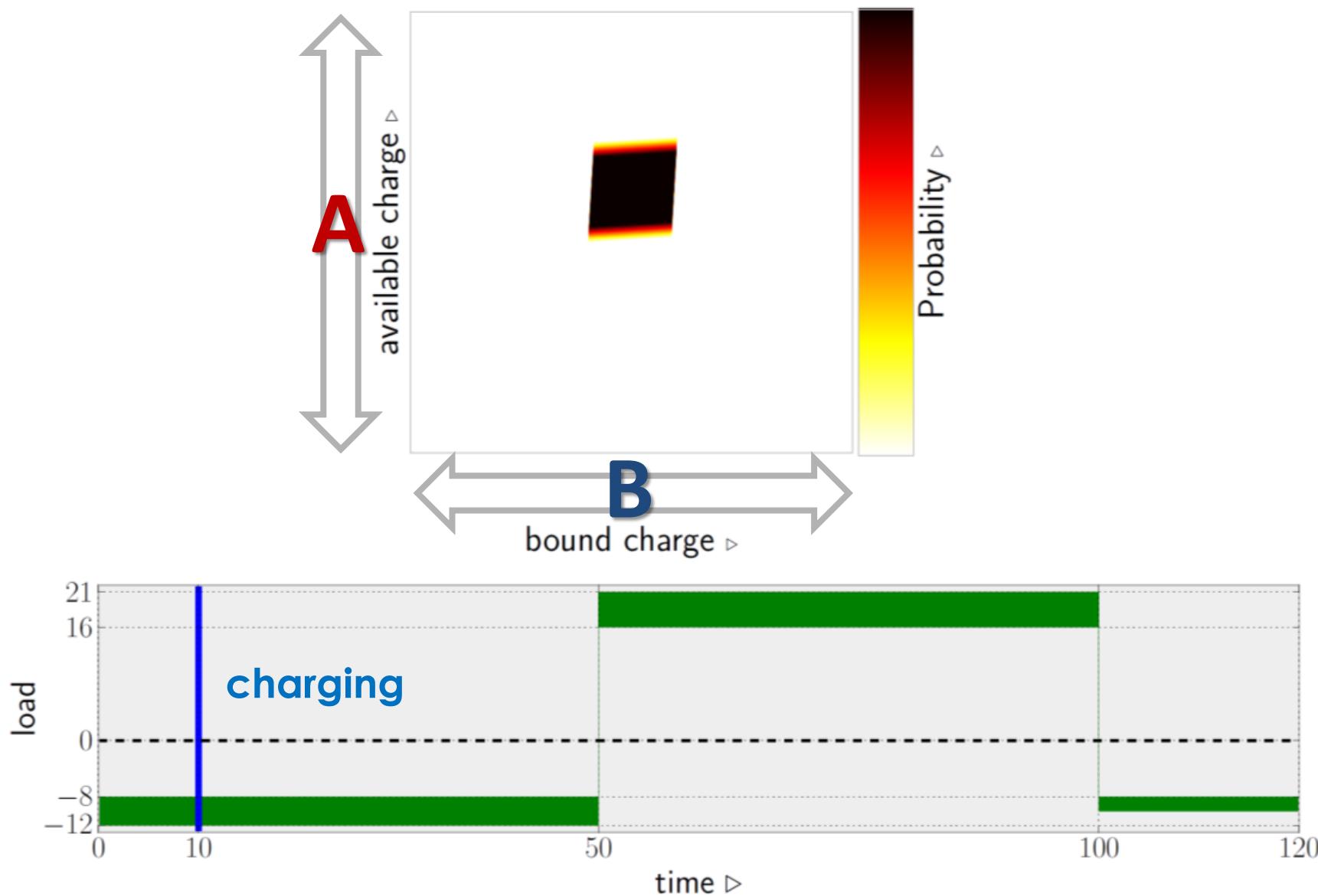
Under the Hood ①



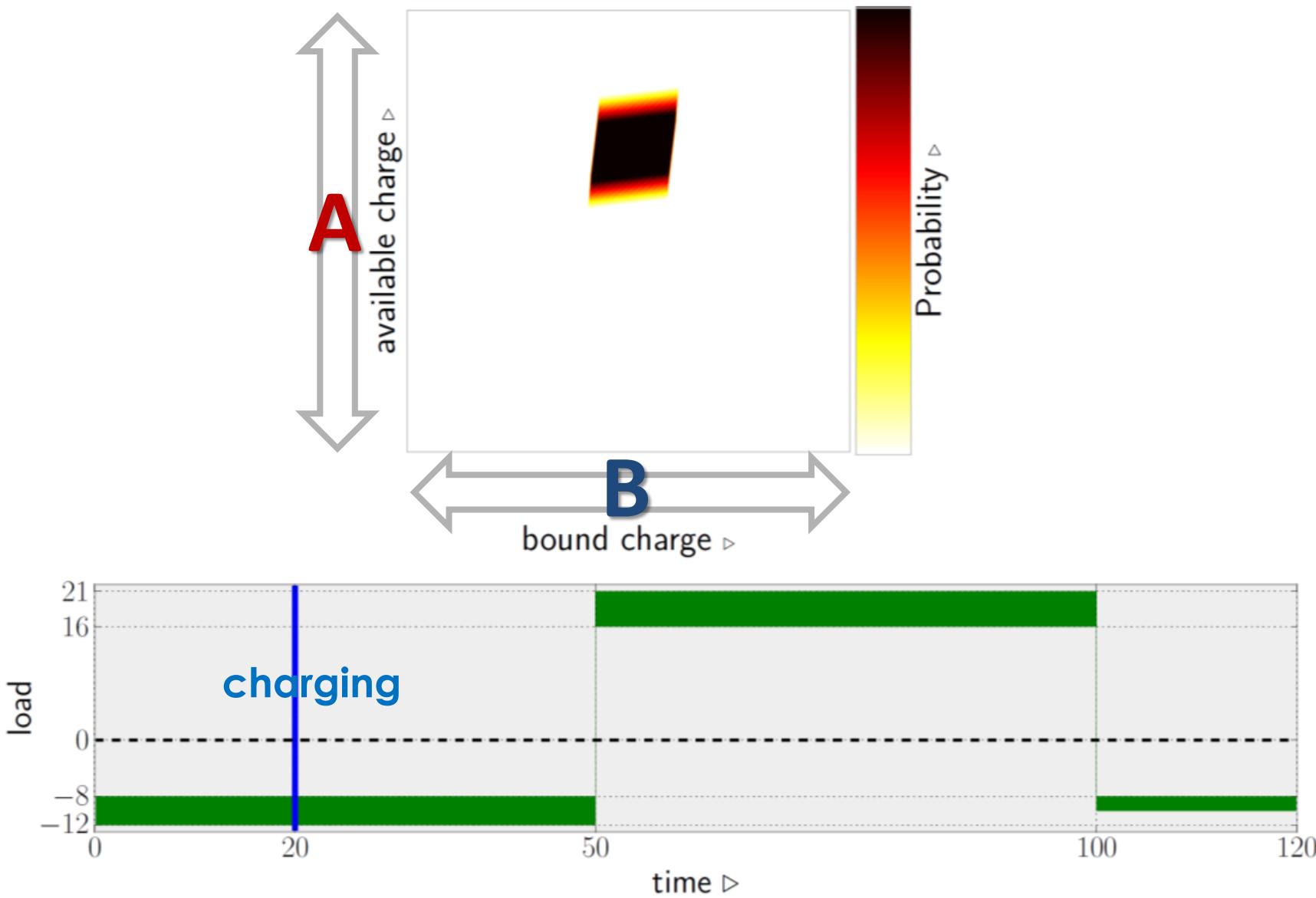
Under the Hood ①



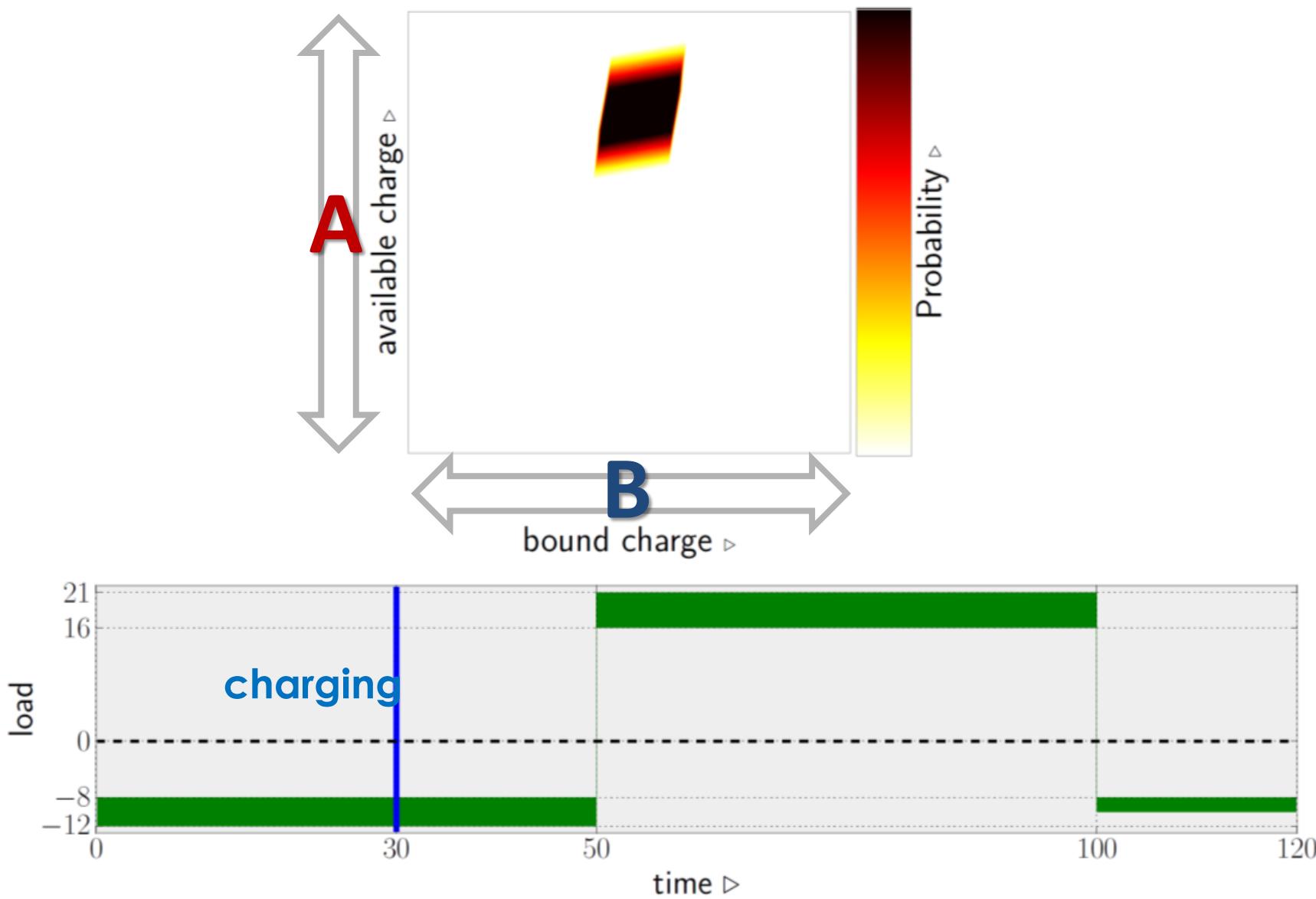
Under the Hood ①



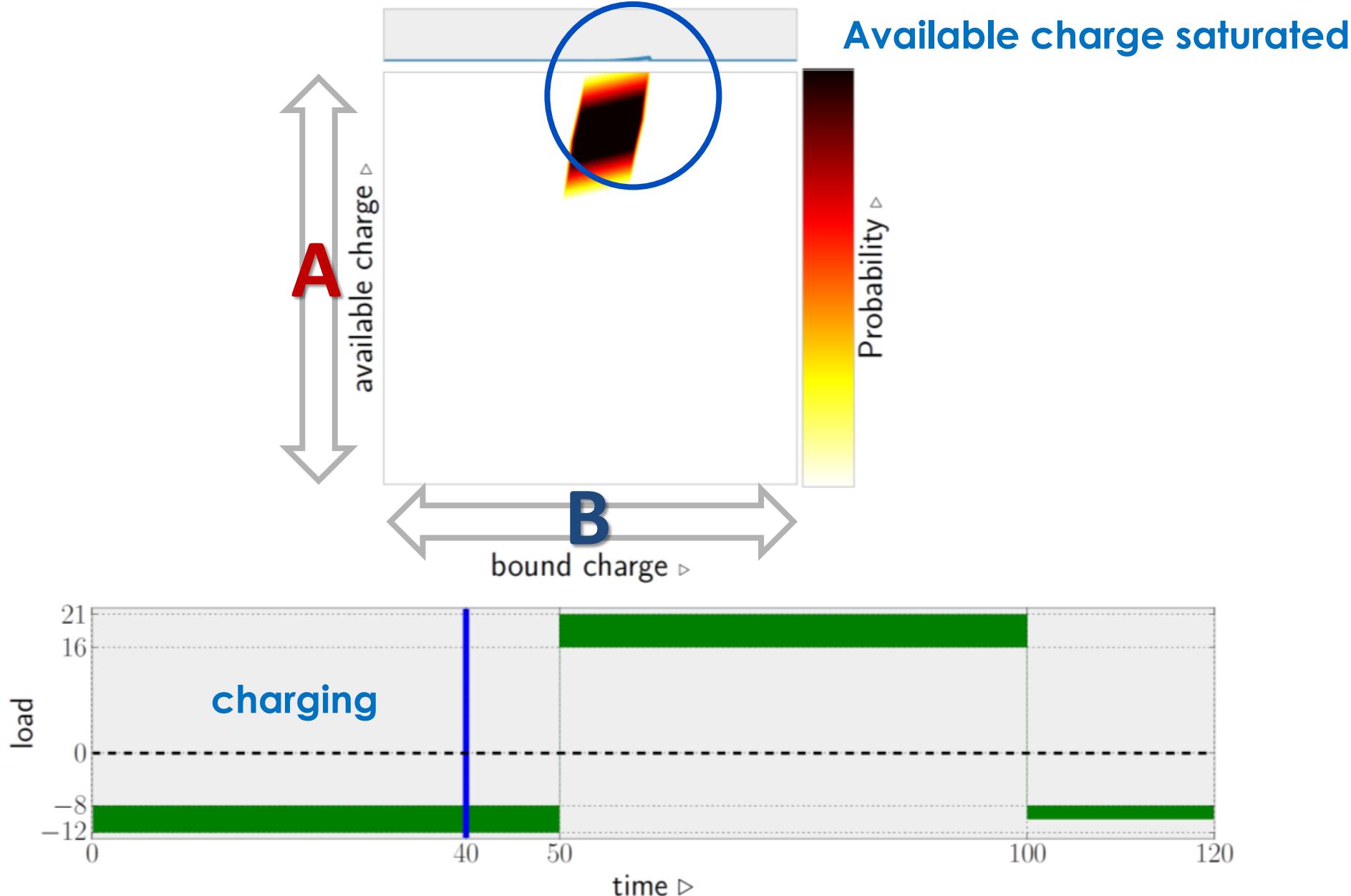
Under the Hood ①



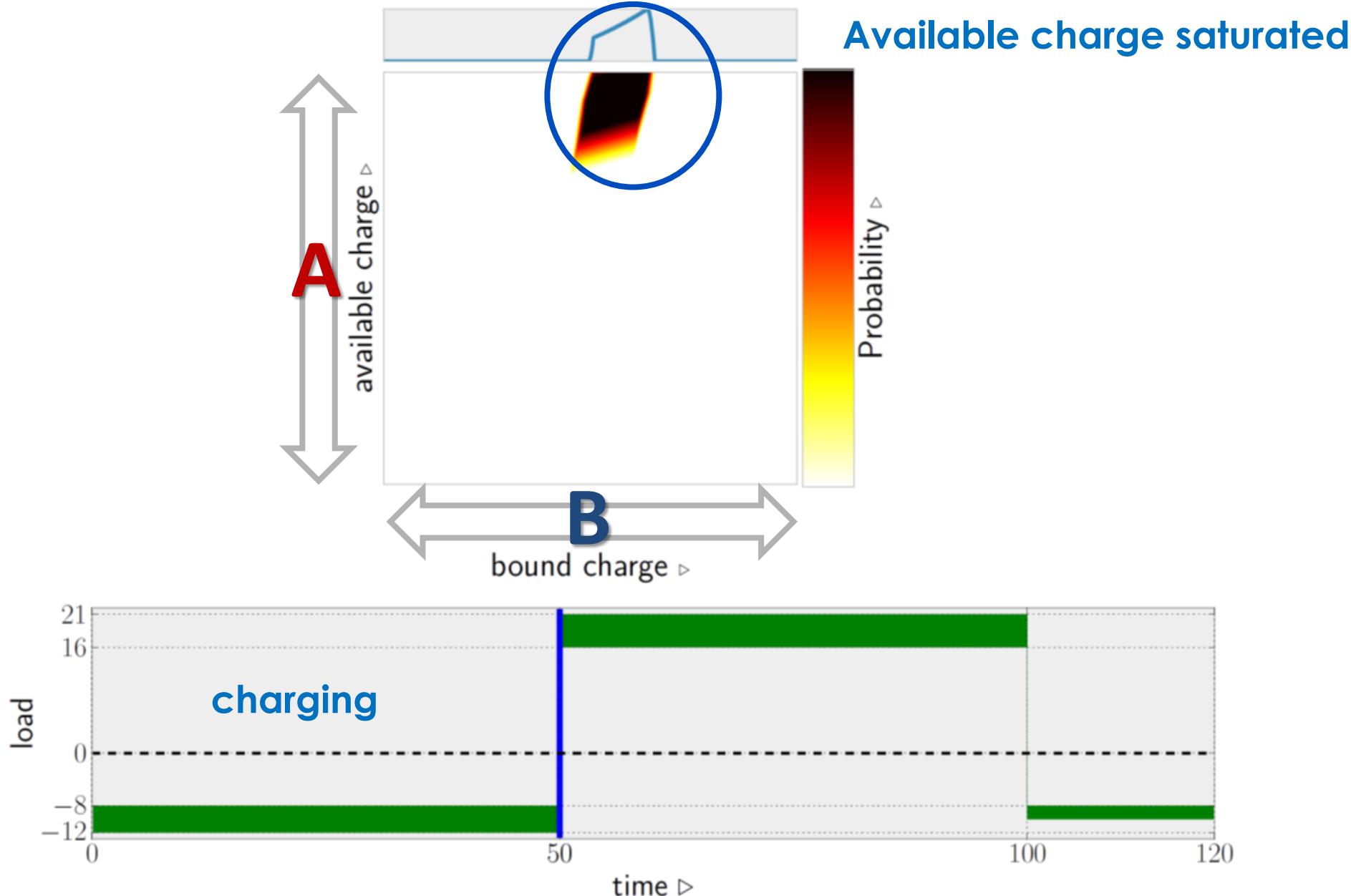
Under the Hood ①



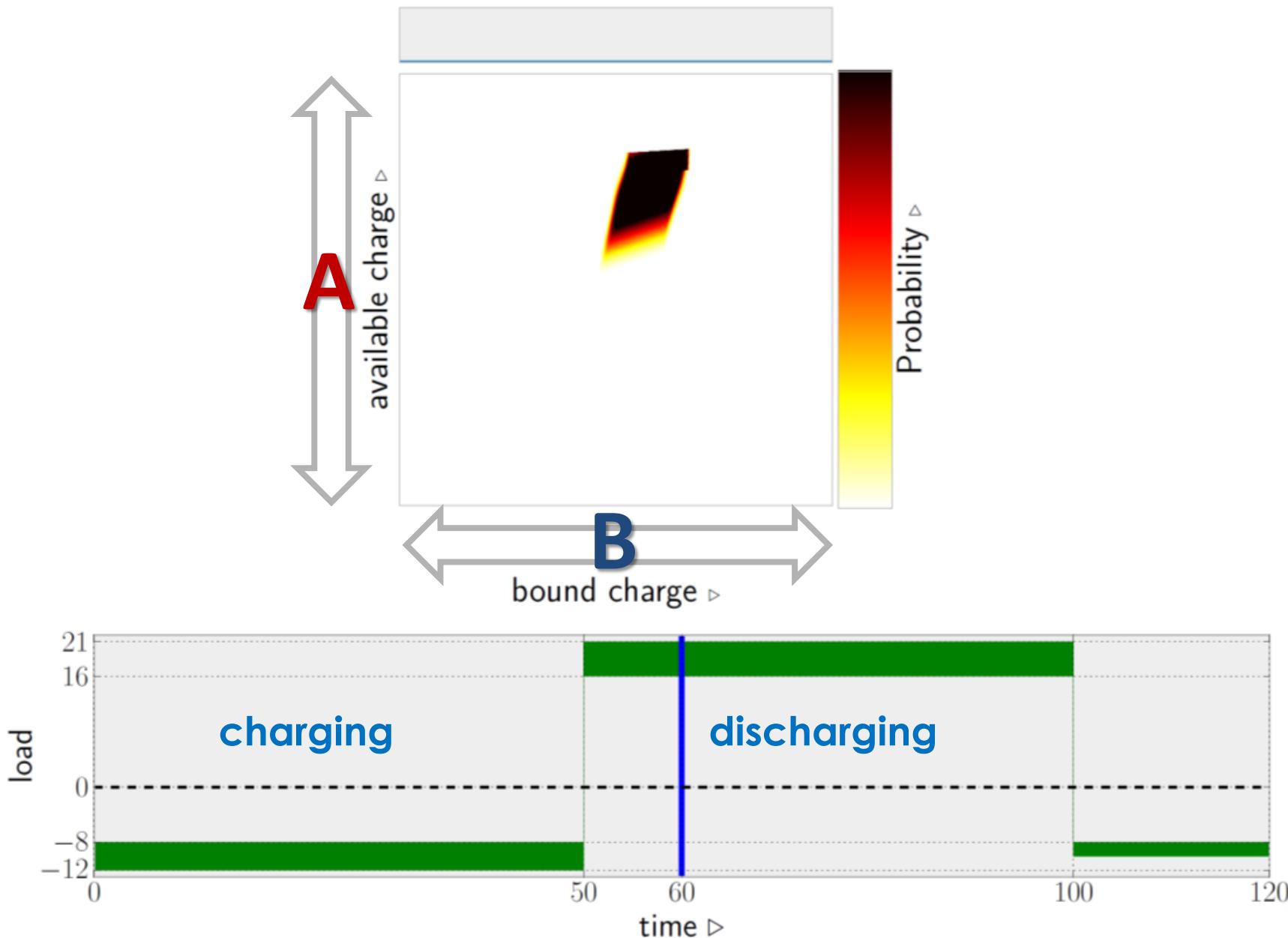
Under the Hood ①



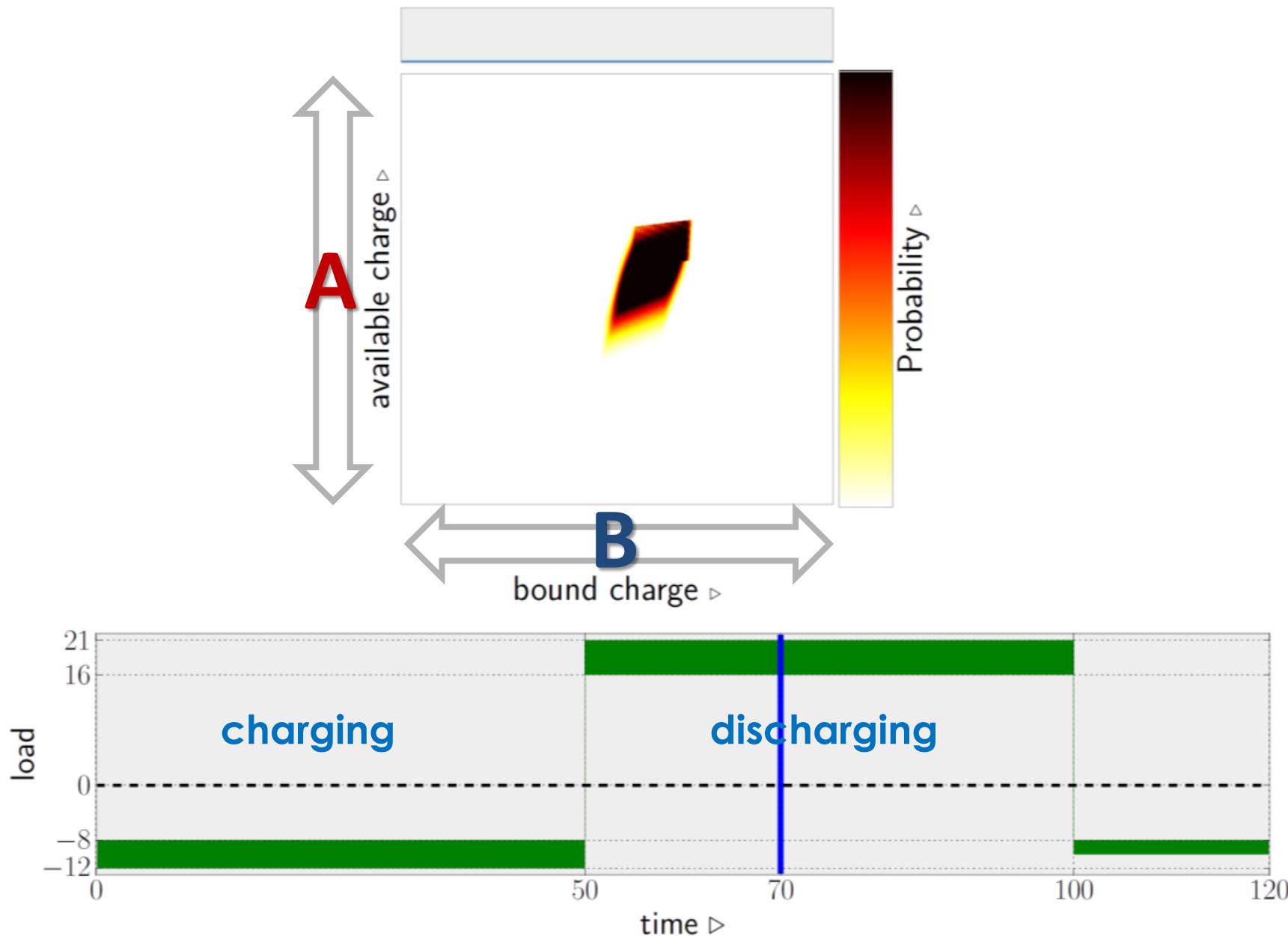
Under the Hood ①



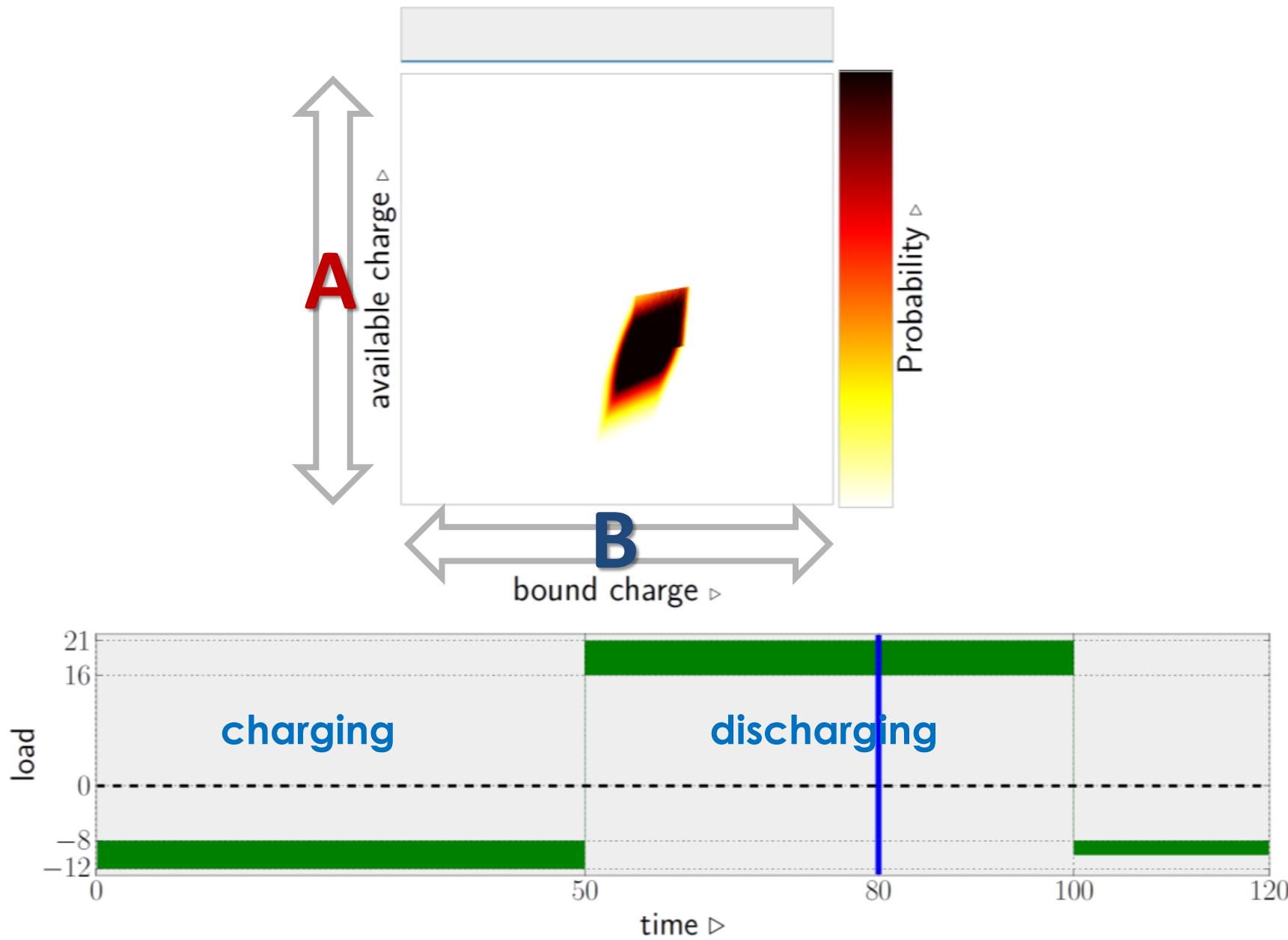
Under the Hood ①



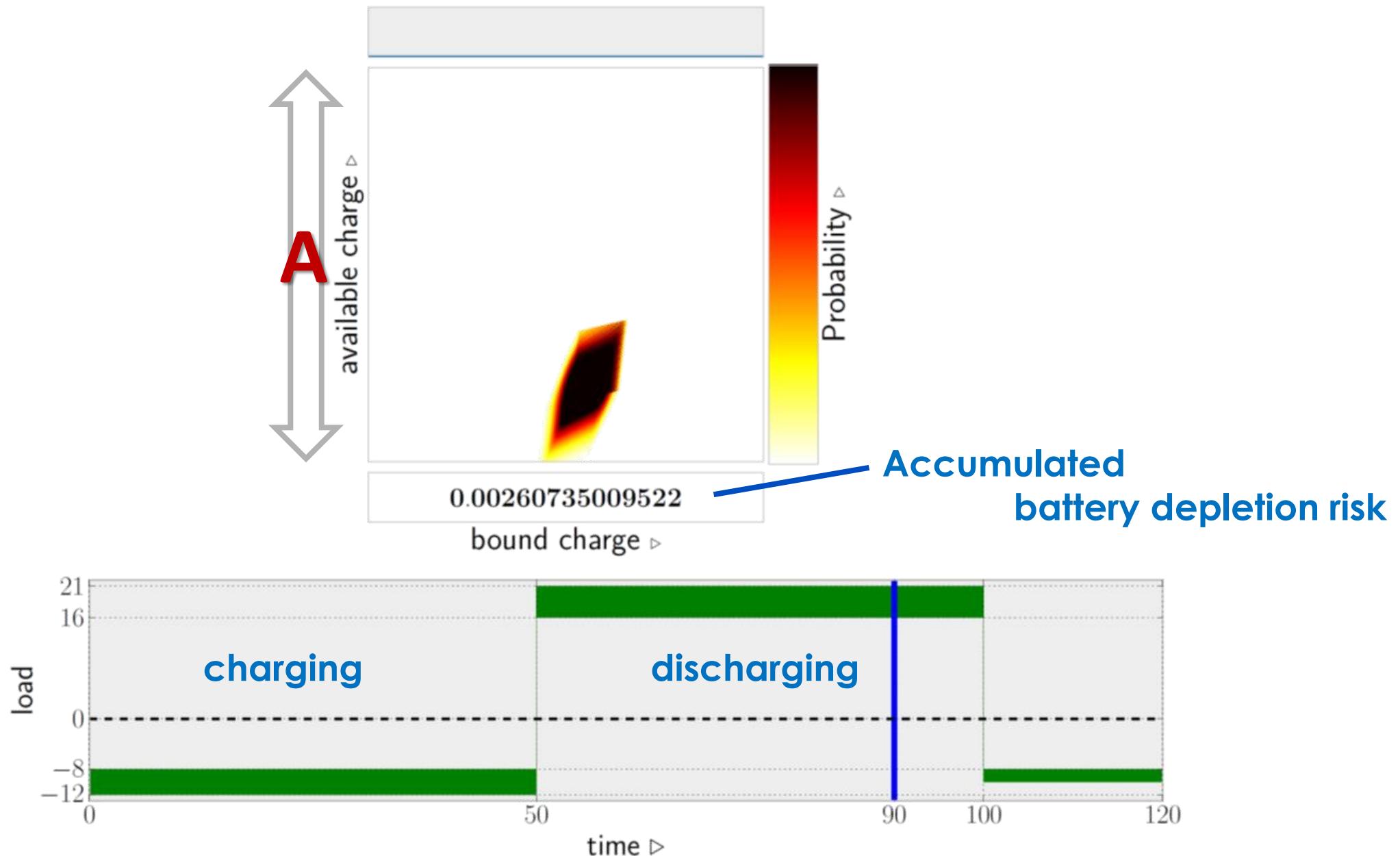
Under the Hood ①



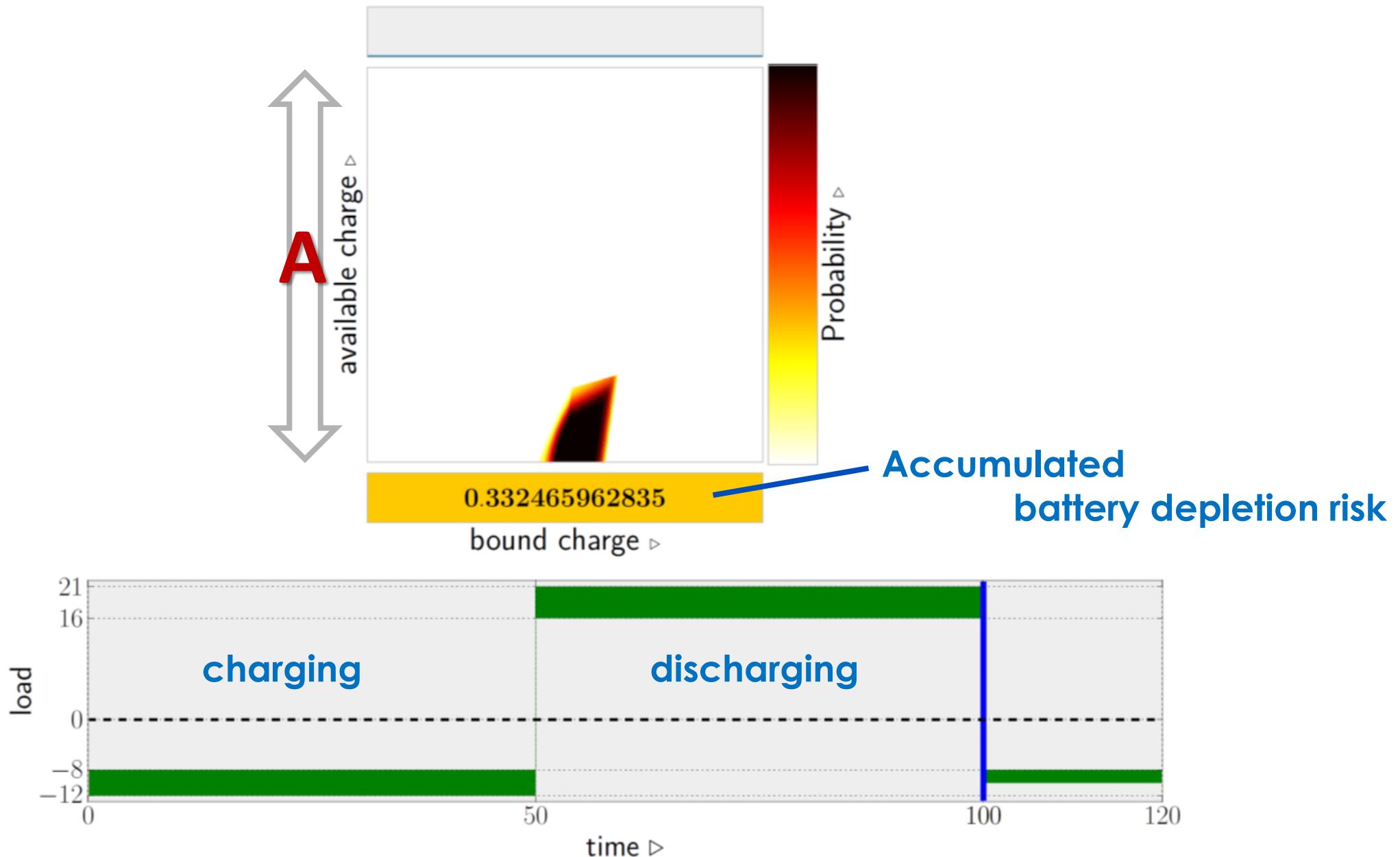
Under the Hood ①



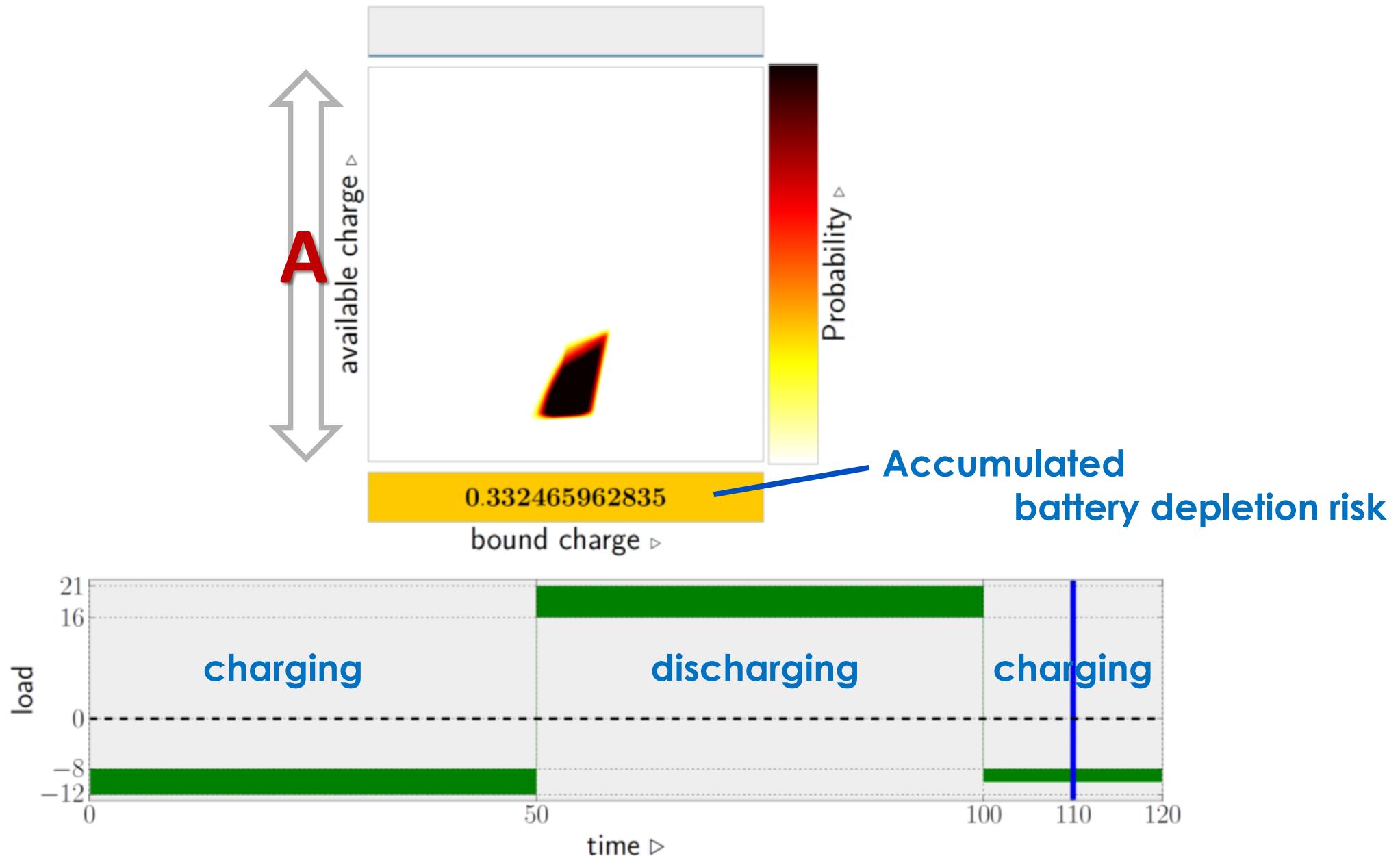
Under the Hood ①



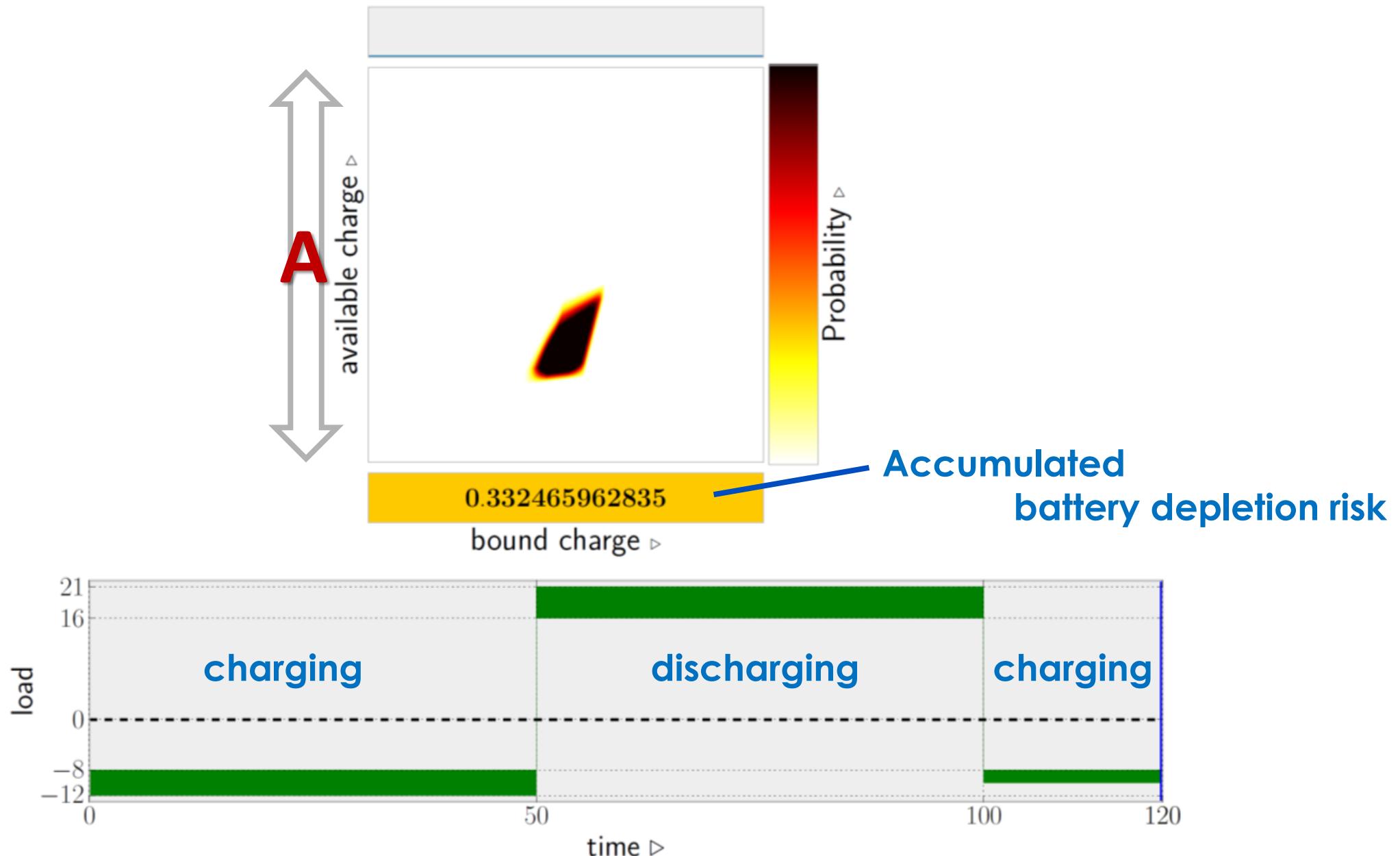
Under the Hood ①



Under the Hood ①



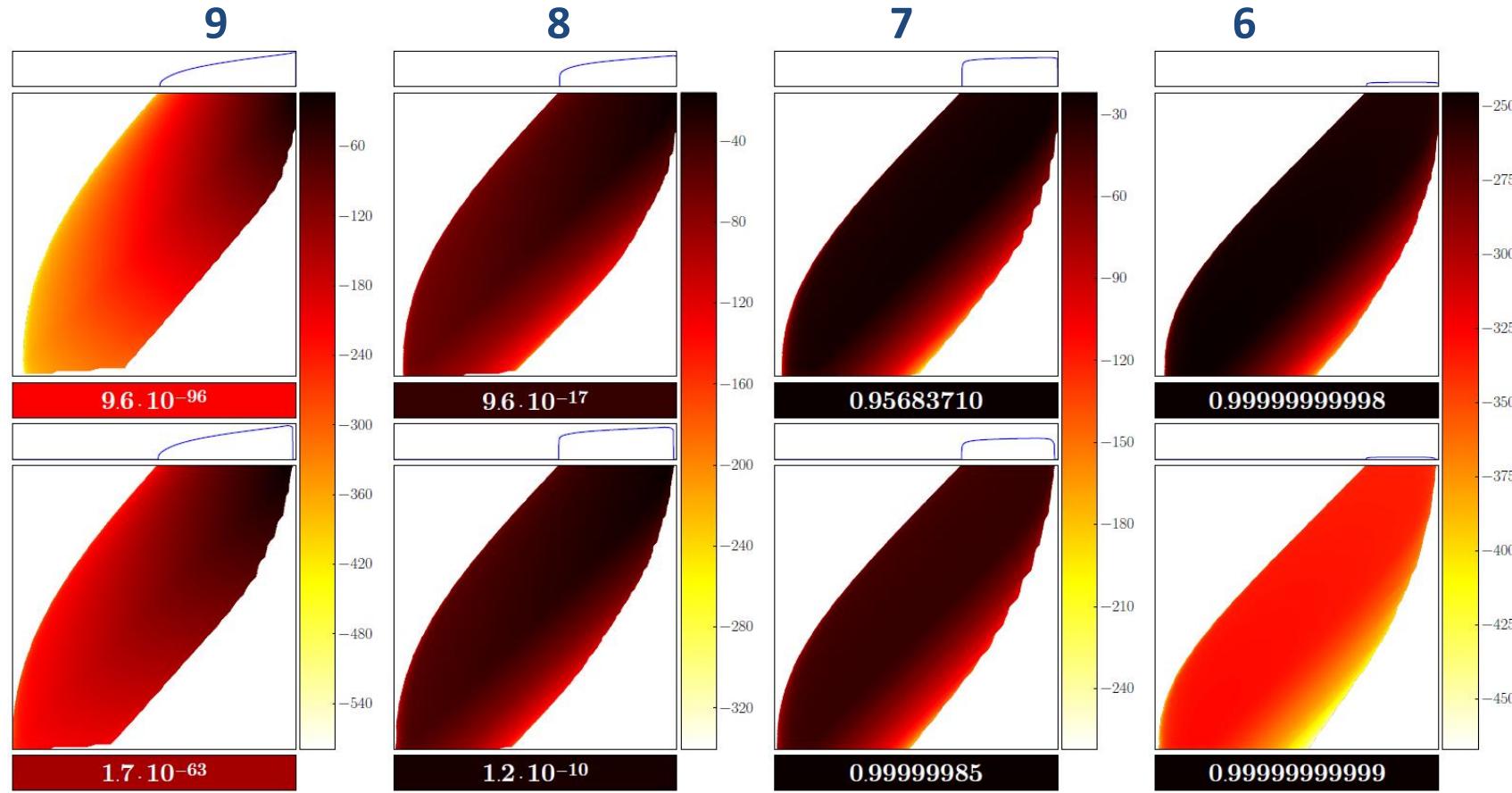
Under the Hood ①



Resilience Analysis for GOMX-1

☞ LITES 4(1)

Number of Solar Panels in Operation



Survival Probability

Time Horizon 1 Year

Probabilistic Load Model

Over-
approx-
imation

Under-
approx-
imation



- 2U – 2 liter
- Shipped in October 2014 with Cygnus CRS-3 towards ISS
- Payloads:
 - Optical communication experiments from NUS
 - Highspeed UHF and SDR receiver



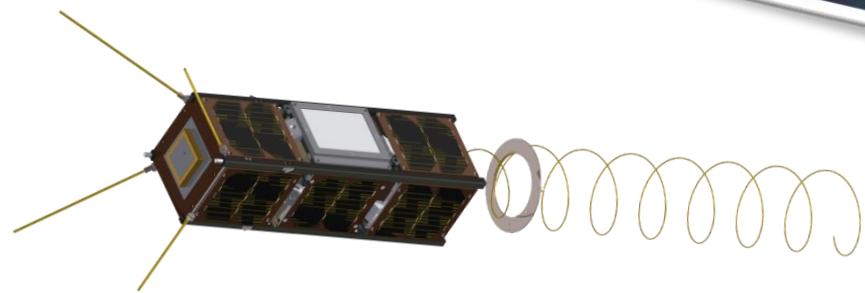
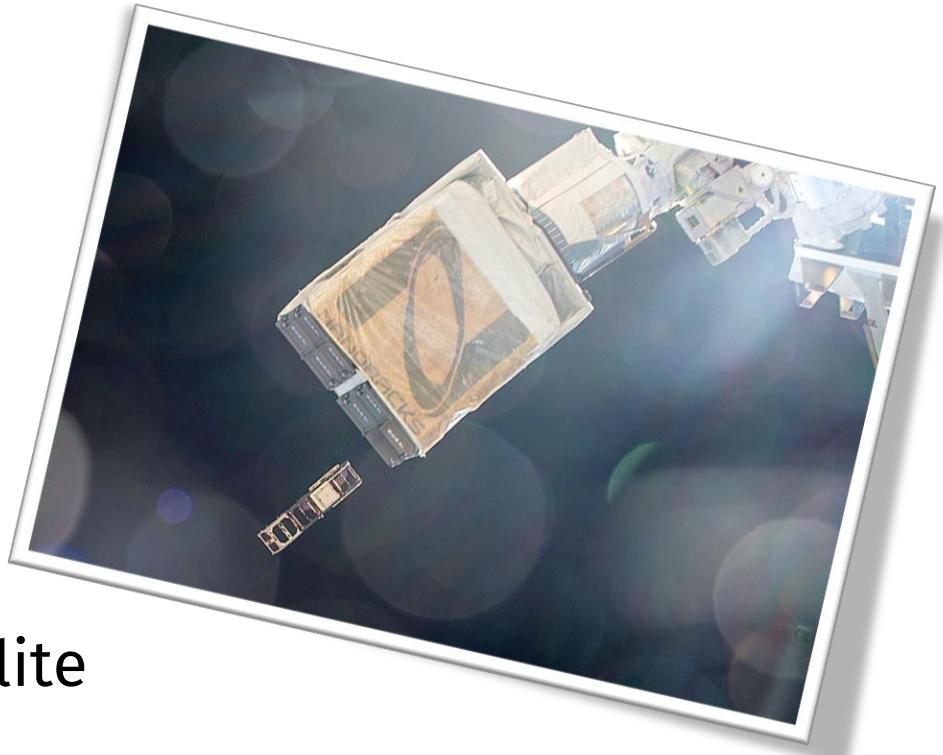
- 2U – 2 liter
- Shipped in October 2014 with Cygnus CRS-3 towards ISS
- Payloads:
 - Optical communication experiments from NUS
 - Highspeed UHF and SDR receiver
- Shipping failed after liftoff



- 2U – 2 liter
- Shipped in October 2014 with Cygnus CRS
- Payloads:
 - Optical communication experiments from space
 - Highspeed UHF and SDR receiver
- Shipping failed after liftoff
- Satellite was recovered from wreckage and returned to manufacturer

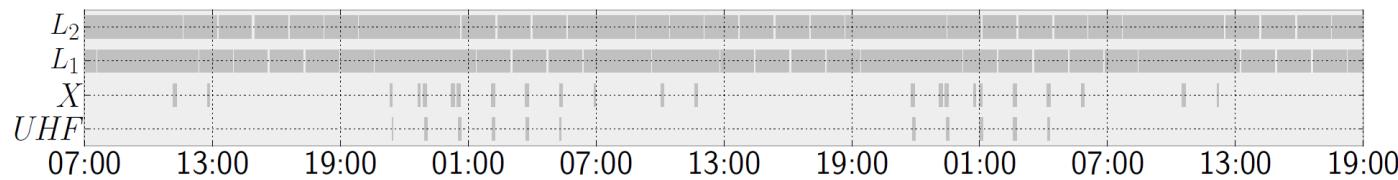


- 3U – 3 liter
- Launched from ISS in October 2015
- Payloads:
 - L-band communication to geostationary satellite
 - X-band transmitter for CNES
 - Highspeed UHF and SDR receiver
- Rotation in 3 dimensions supported – and needed.
- Deorbited in fall 2016.



When to do what?

Options available



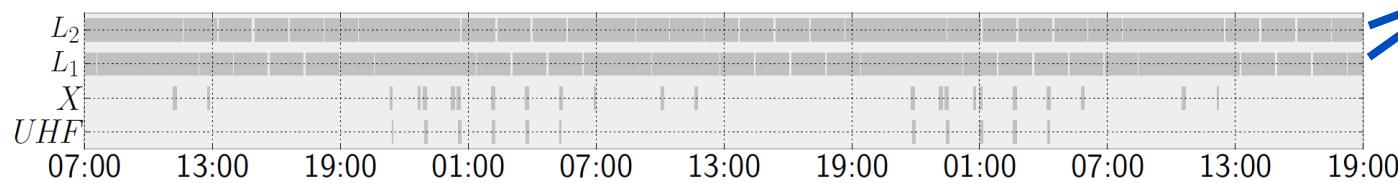
March 20/21, 2016

time ▷



When to do what?

Options available



March 20/21, 2016

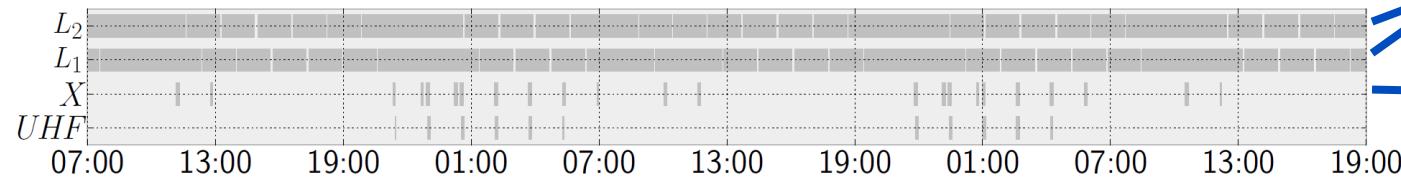
time ▶

Listen to geostationary satellites



When to do what?

Options available



March 20/21, 2016

time ▶

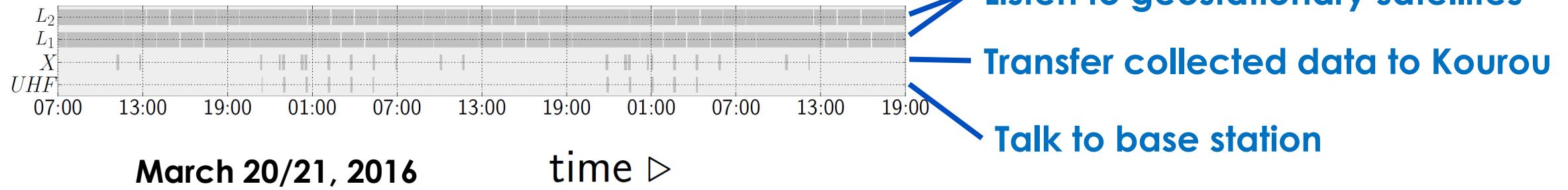
Listen to geostationary satellites

Transfer collected data to Kourou



When to do what?

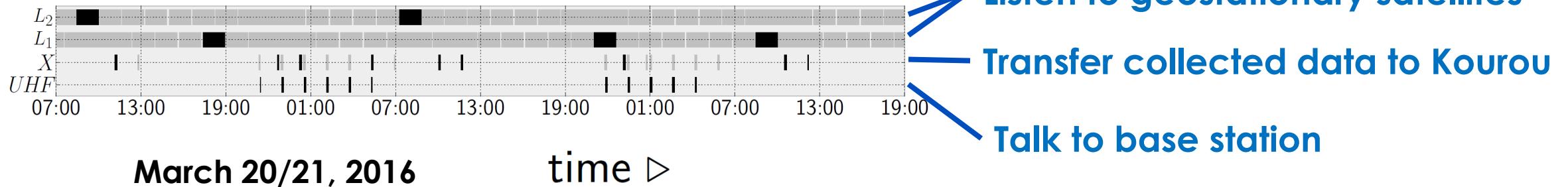
Options available



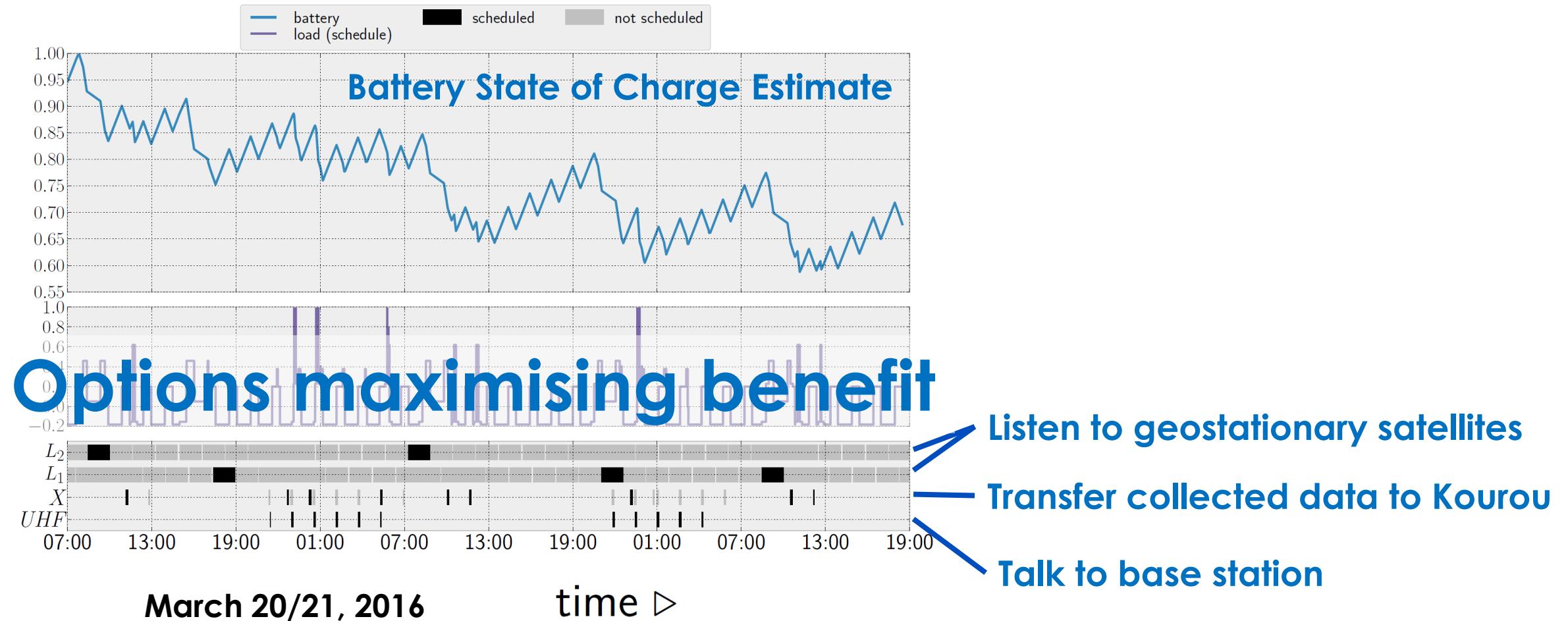
When to do what?

■ scheduled ■ not scheduled

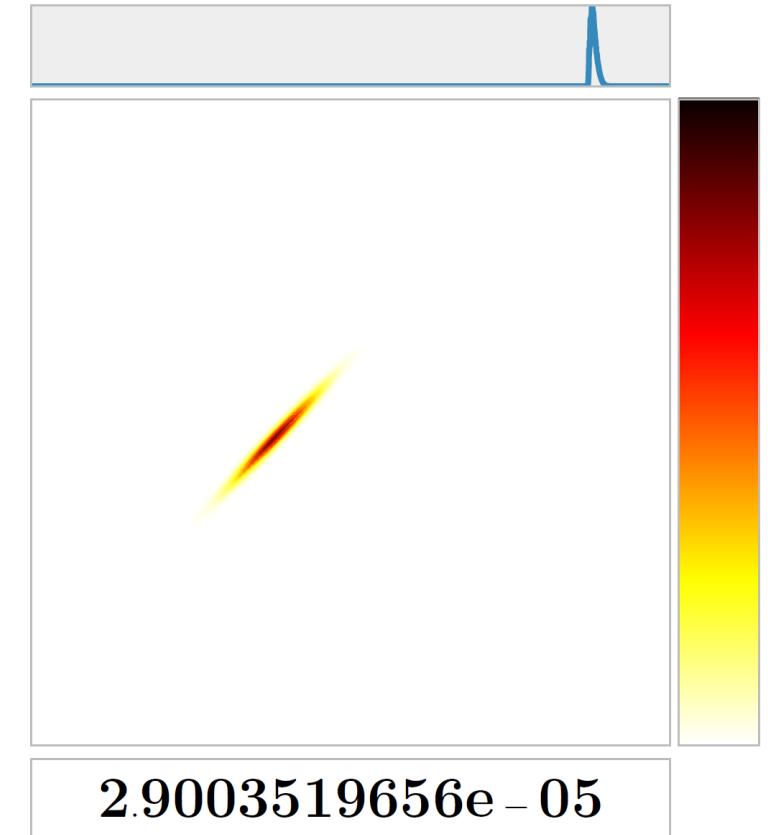
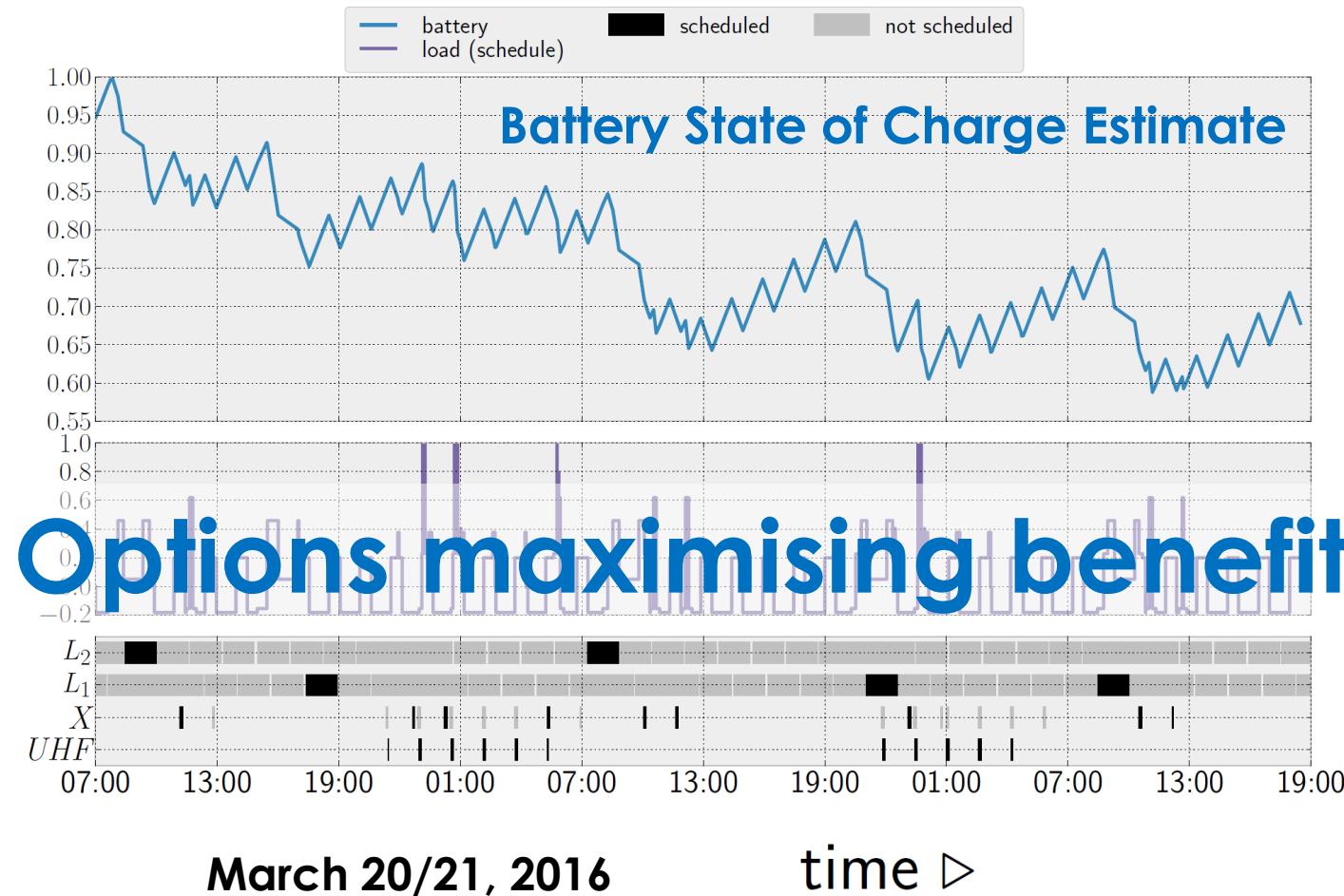
Options maximising benefit



When to do what?



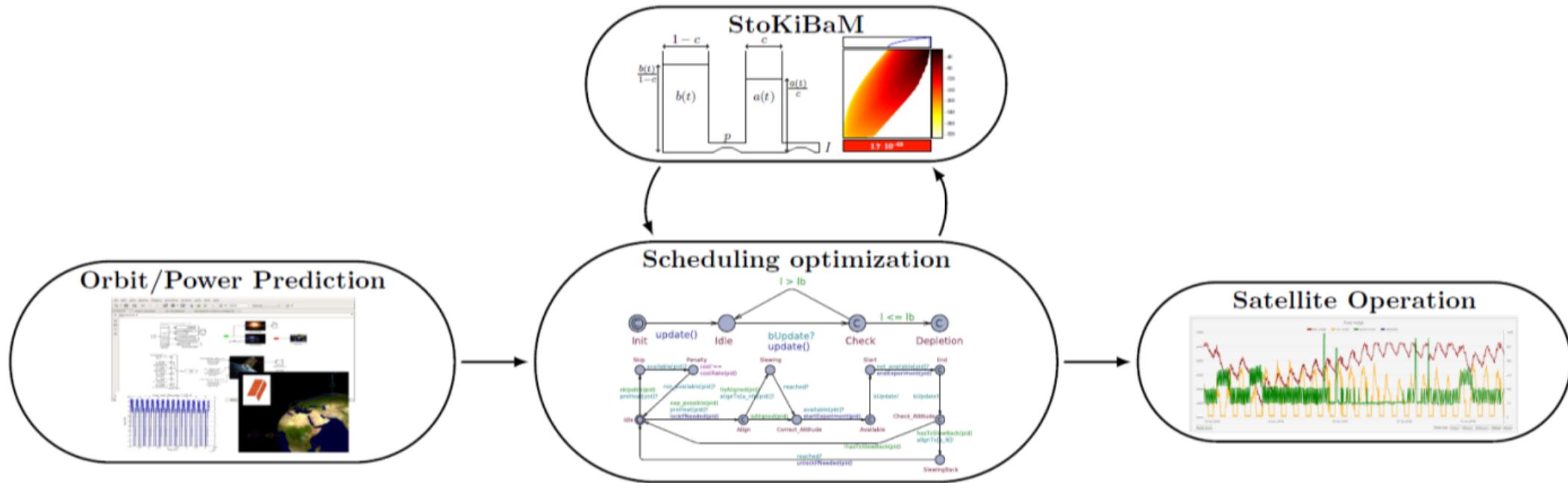
When to do what?



Battery Depletion Risk Estimate



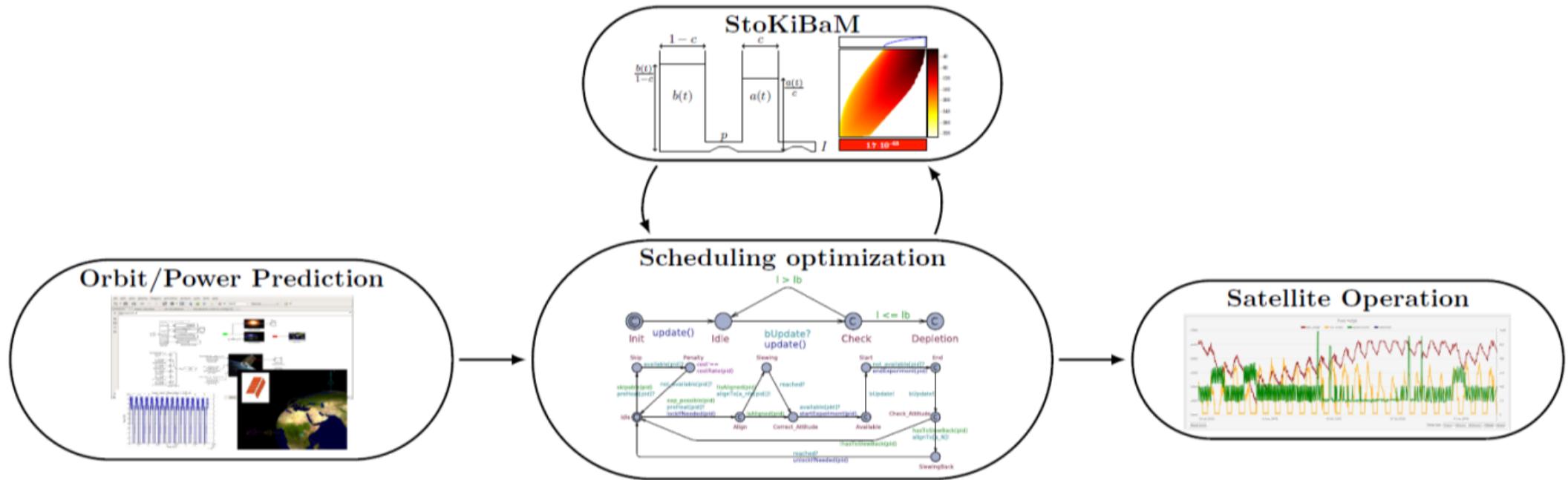
Under the Hood ②



1. Compute schedule \mathbf{S} for a couple of days
2. Evaluation using stochastic KiBaM
 - 2.1 If depletion risk small enough \Rightarrow *accept \mathbf{S}*
 - 2.2 If depletion risk too high \Rightarrow *exclude \mathbf{S}* then goto 1



Under the Hood ②



Priced Timed Automata Model Checking

1. Compute schedule S for a couple of days
2. Evaluation using stochastic KiBaM
 - 2.1 If depletion risk small enough \Rightarrow *accept S*
 - 2.2 If depletion risk too high \Rightarrow *exclude S* then goto 1



Under the Hood ②

Network of LPTA

- ▶ **Jobs**
 - ▶ take or skip opportunity
 - ▶ positioning, preheating
 - ▶ powering actual device
- ▶ **Battery (linear)**
 - ▶ piecewise constant loads
 - ▶ Safe Mode threshold
 - ▶ take decisions based on SoC
- ▶ **Background Load**
 - ▶ ADS-B module
 - ▶ attitude control (not full power)
 - ▶ background computations
- ▶ **Sun**
 - ▶ Eclipse
 - ▶ Insolation

Cost Model

- ▶ Accumulate cost whenever a job windows is **not** taken
- ▶ Skipping UHF is very expensive (needs to be scheduled)
- ▶ Skipping 2 X-Band jobs is as expensive as skipping 1 L-Band job.
- ▶ Costs for skipping either geo-stat. satellite are equal.

Reachability Objectives

- ▶ $\exists \Diamond \#orbits = \phi \wedge SoC \geq \theta$



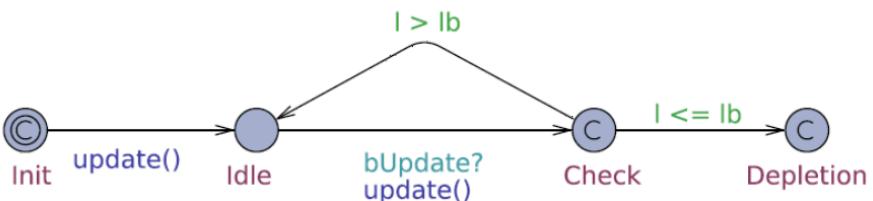
Under the Hood ②

Network of I PTA

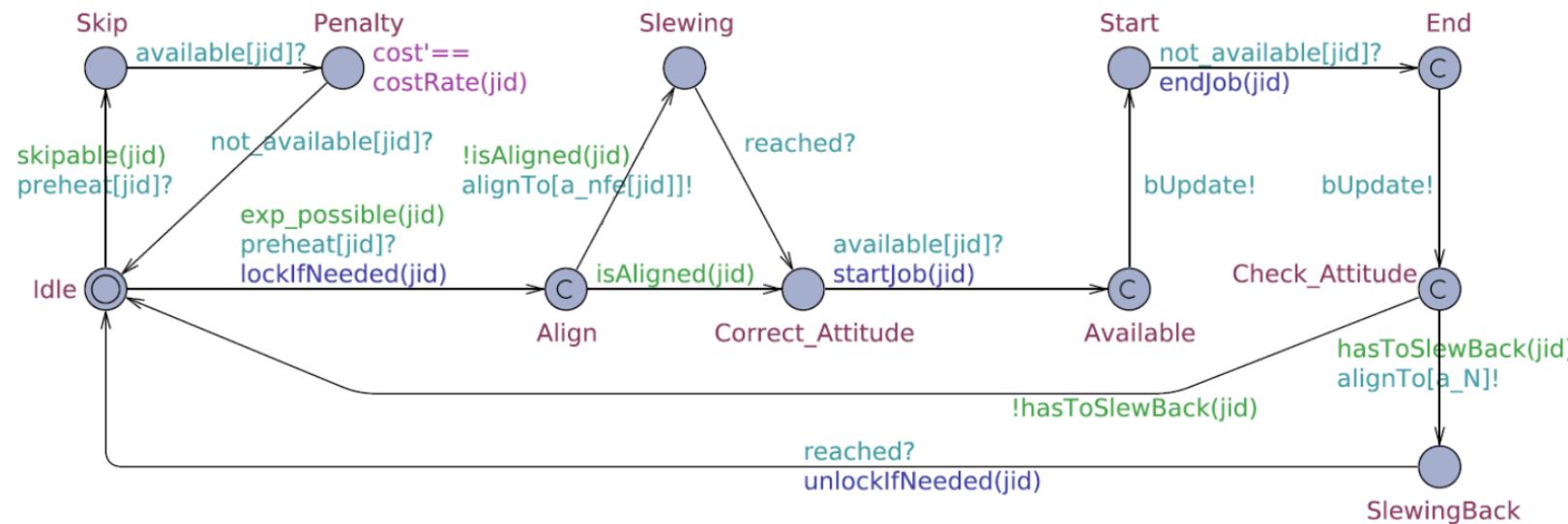
Cost Model

Concrete PTAs

Battery



Job



late cost whenever a job is **not** taken

; UHF is very expensive
o be scheduled)

; 2 X-Band jobs is as
e as skipping 1 L-Band job.
r skipping either geo-stat.
are equal.

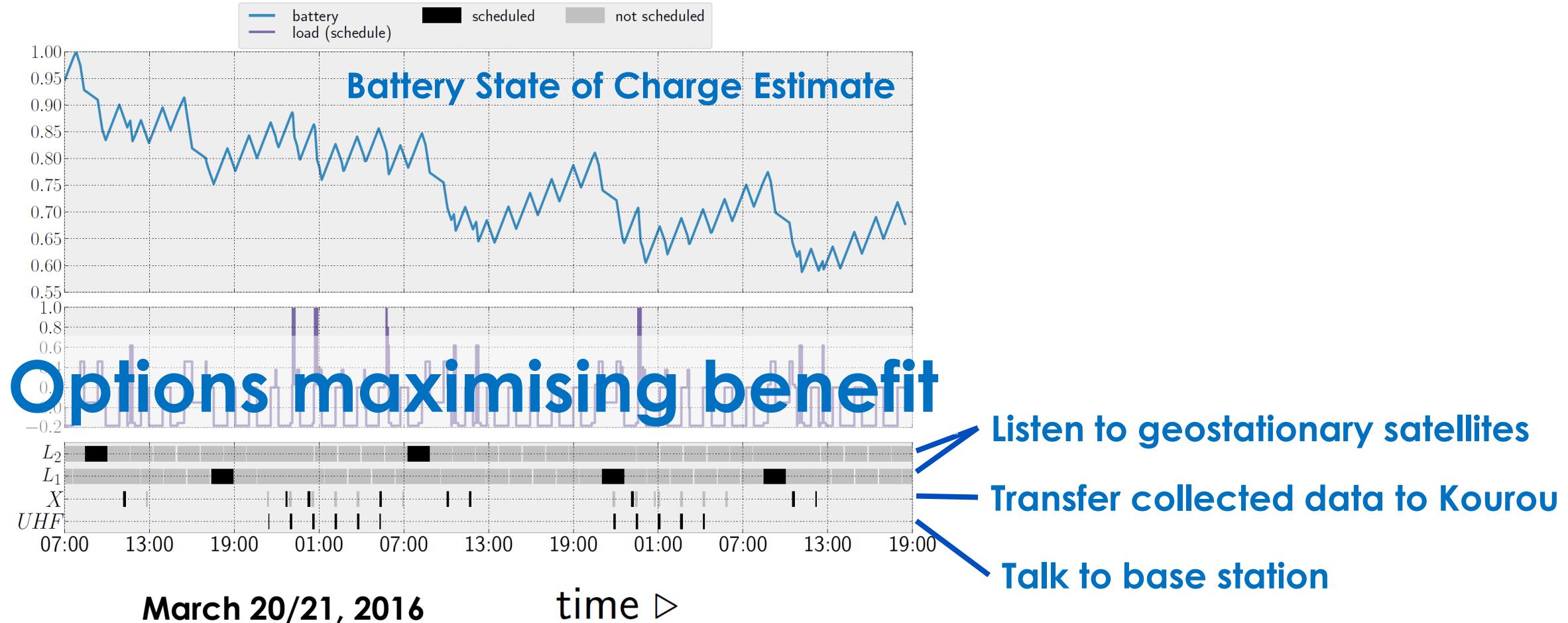
Objectives

$$\text{its} = \phi \wedge \text{SoC} \geq \theta$$



When to do what?

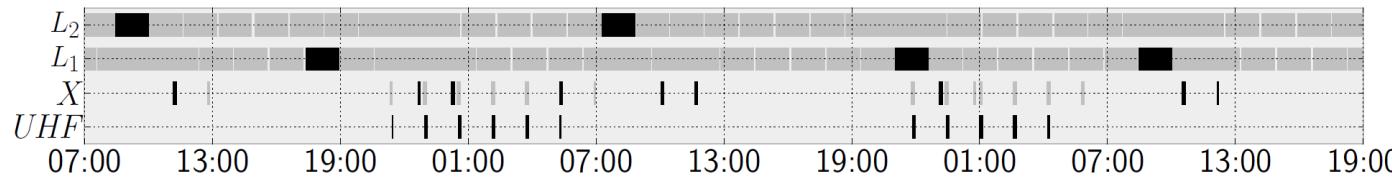
☞ [FM 2016](#)
☞ [Acta Astronautica 151](#)



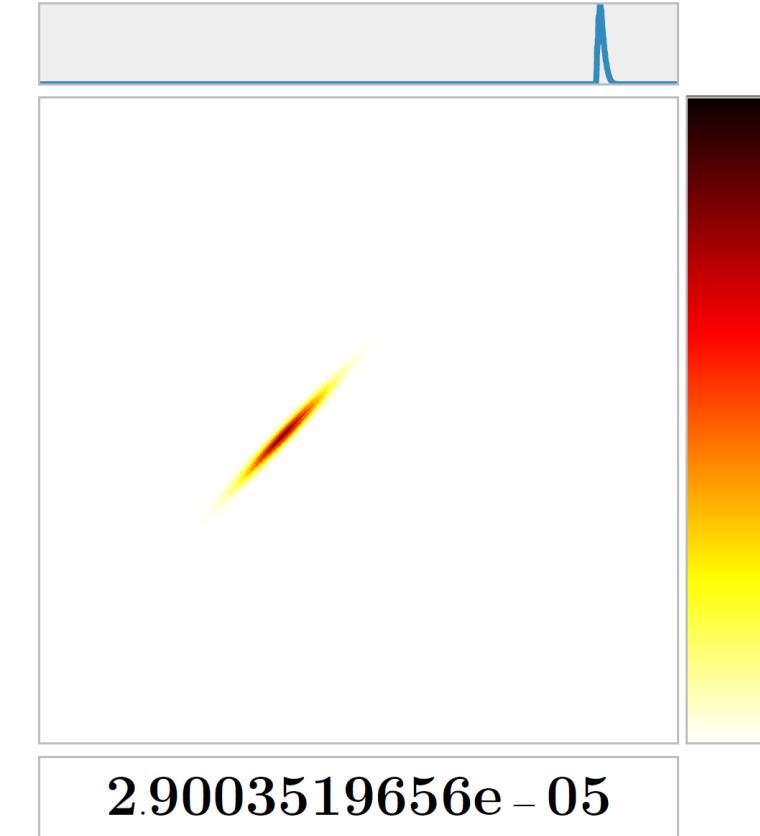
In-Orbit Demonstration

FM 2016

Acta Astronautica 151



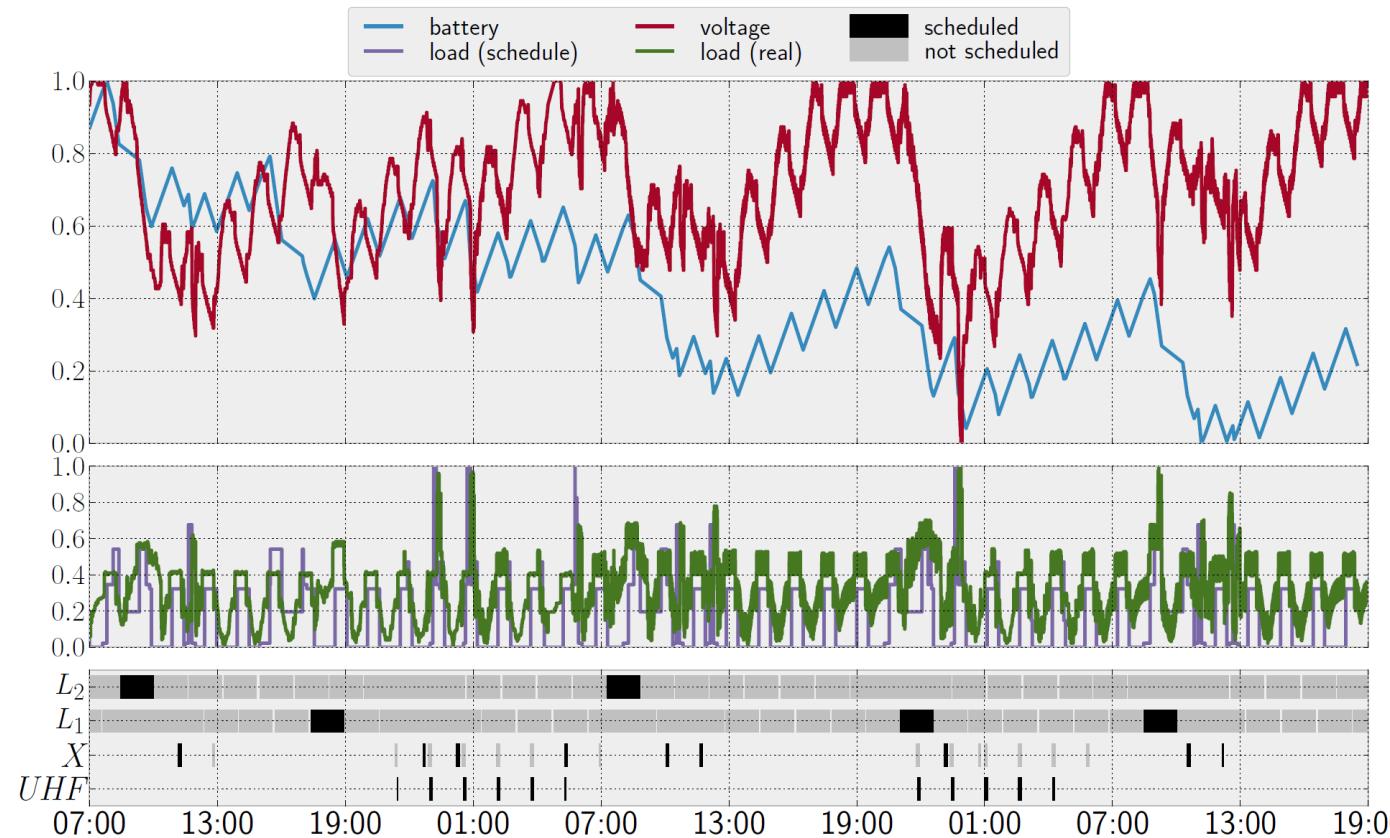
March 20/21, 2016



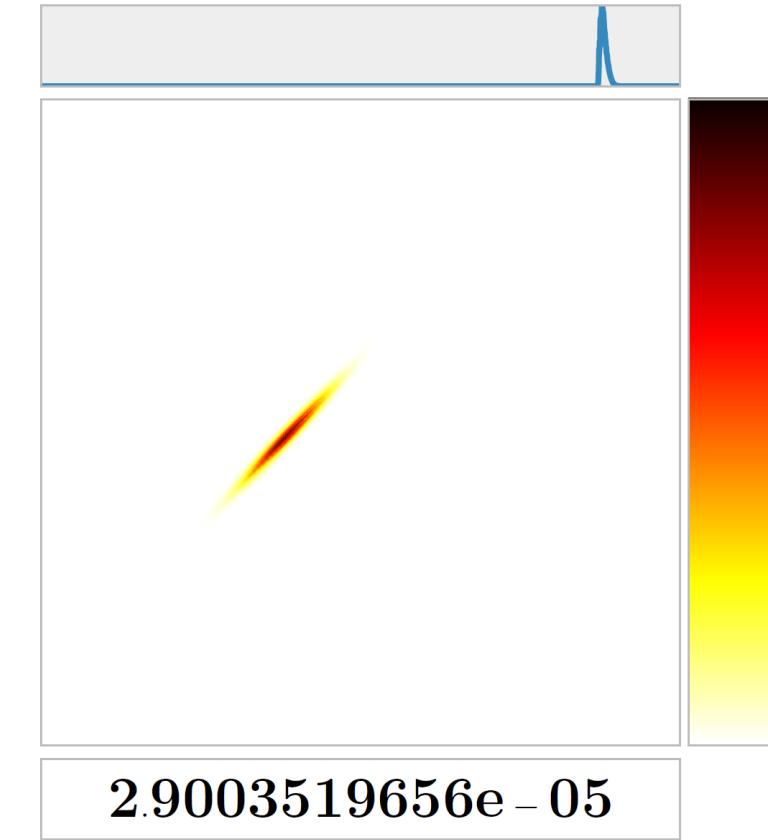
In-Orbit Demonstration

FM 2016
Acta Astronautica 151

Observed Behaviour



March 20/21, 2016





GOMSPACE

- Twins of 6U – 6 liter each

- Launched in February 2018.

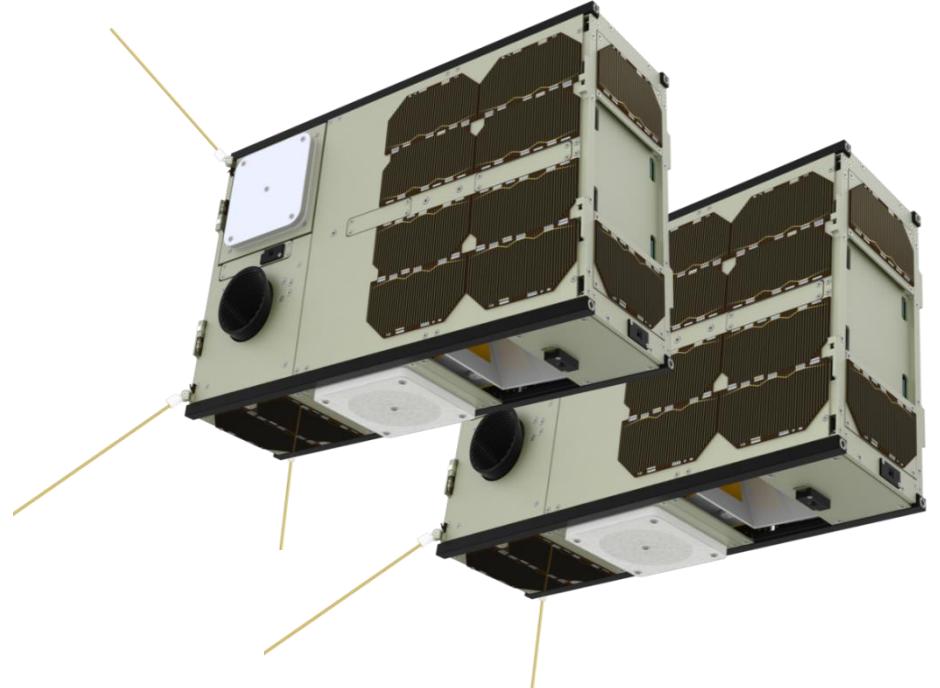
- Targetting in-orbit validation of technology for larger LEO constellations.

- Inter-satellite radio links (ISL),

- Cold gas thruster, ...

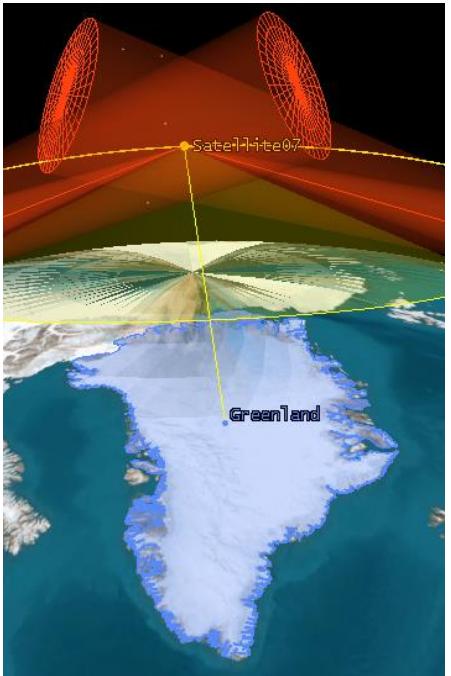
- Focus on support for flexible payload.

- Experimental platform for dynamic load scheduling.



Ulloriaq Constellation

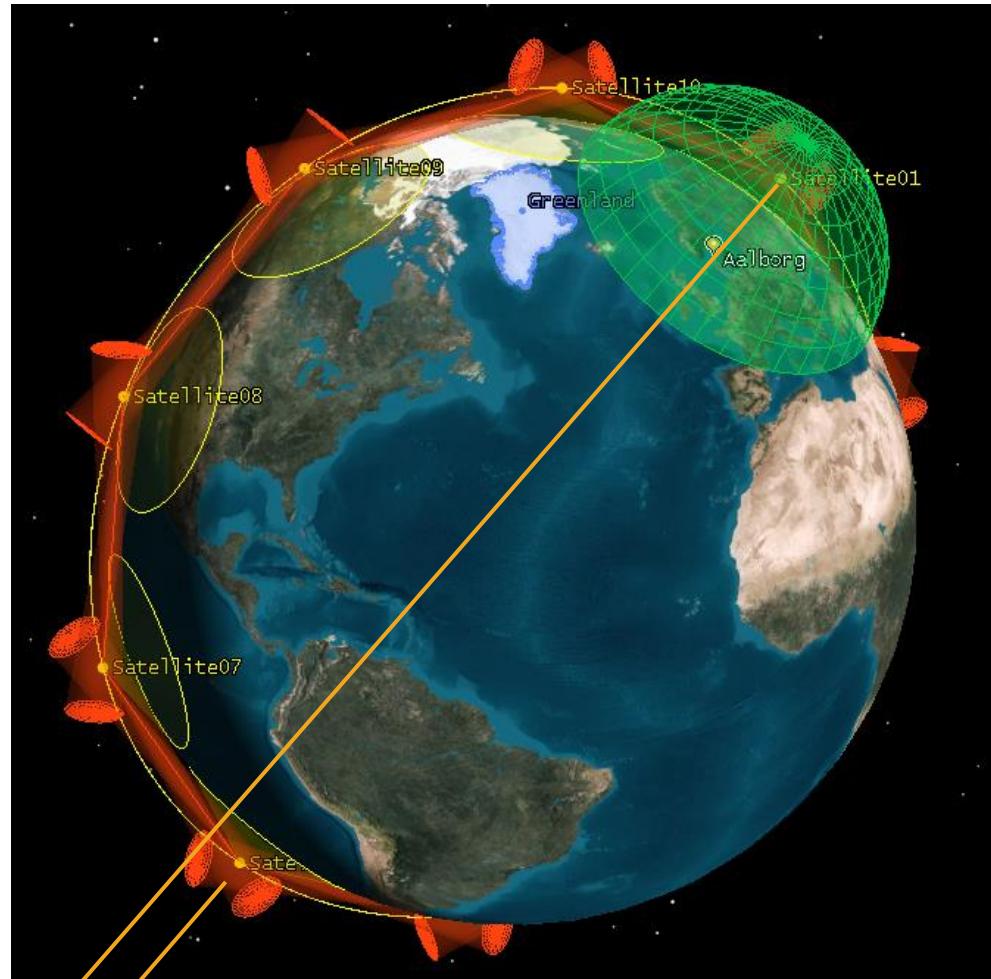
10 GOMX-4-Like Satellites in a Ring



- Data collection over Greenland
- Delivery to Aalborg, Denmark
- Near-polar orbit provides almost perpetual visibility over Greenland

Greenland to Satellites	Satellites to Satellites	Satellites to Aalborg
10 kbps	10 kbps	100 Mbps (HSL)

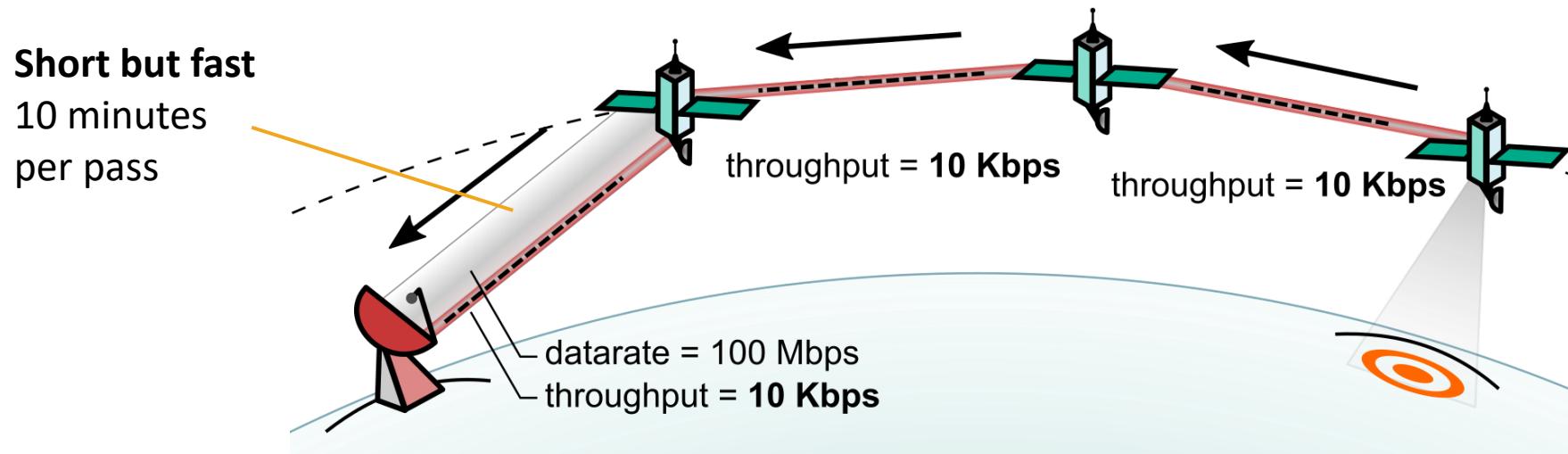
X-Band High Speed Link
in Sat1
and Sat6



Ulloriaq Constellation

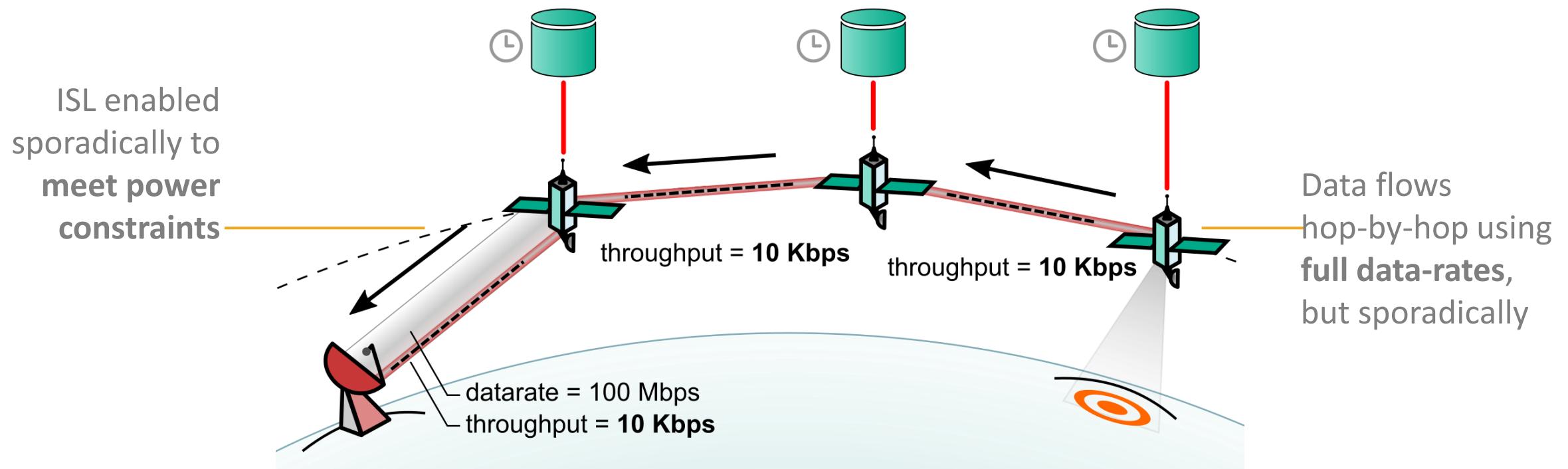
Power and Data Flow Constraints

- **Power constraints**
 - ISL transponders drain the batteries almost instantly
- **Data flow constraints**
 - ISLs are bottleneck if presupposing end-to-end-connectivity



Store-Carry-and-Forward

- Power and data flow constraints ask for **Store-Carry-and-Forward**



Battery-Aware Contact Plan Design

When to communicate – based on **data flow** and **battery charge**



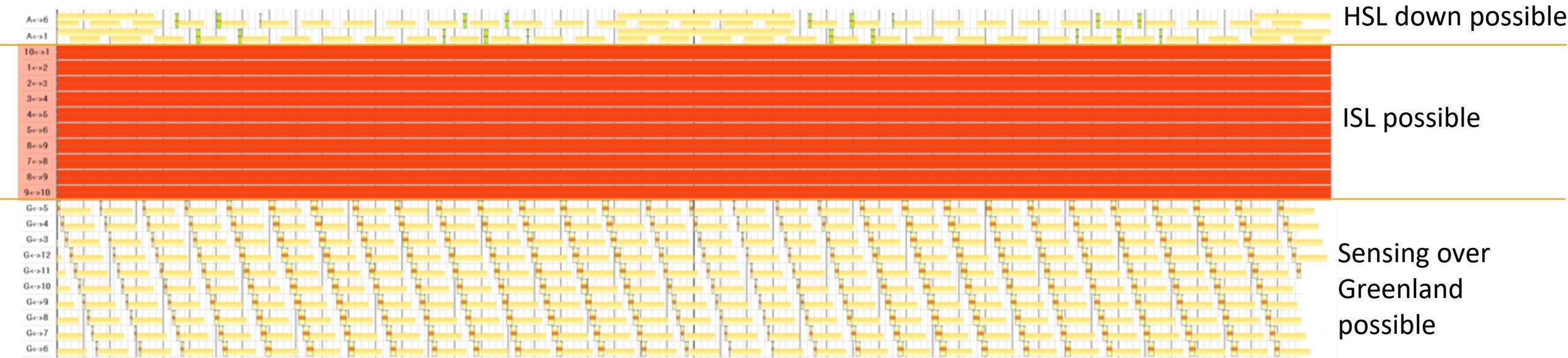
Battery-Aware Contact Plan Design

When to communicate – based on **data flow and battery charge**



Battery-Aware Contact Plan Design

When to communicate – based on **data flow and battery charge**

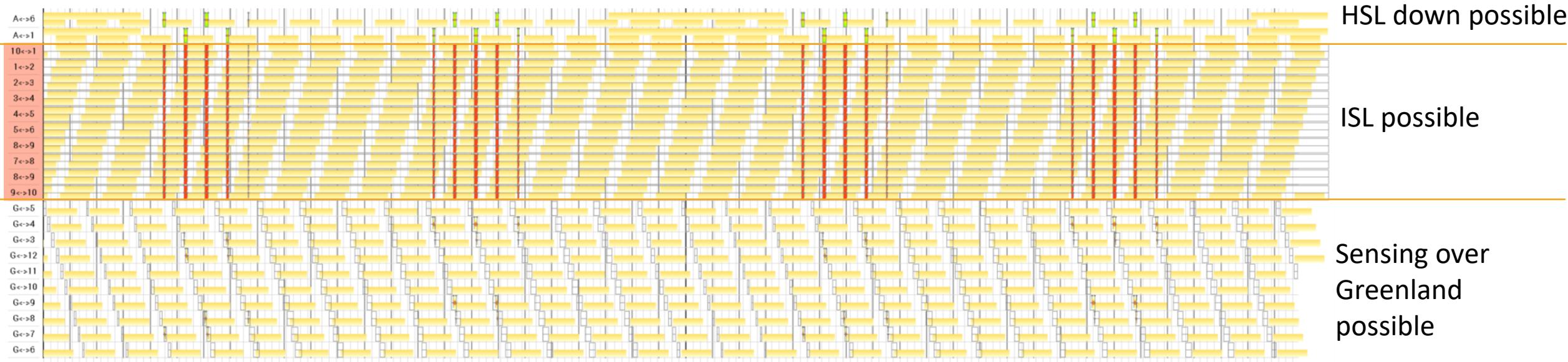


If each satellite has unlimited battery charge
and communication happens whenever possible



Battery-Aware Contact Plan Design

When to communicate – based on **data flow and battery charge**



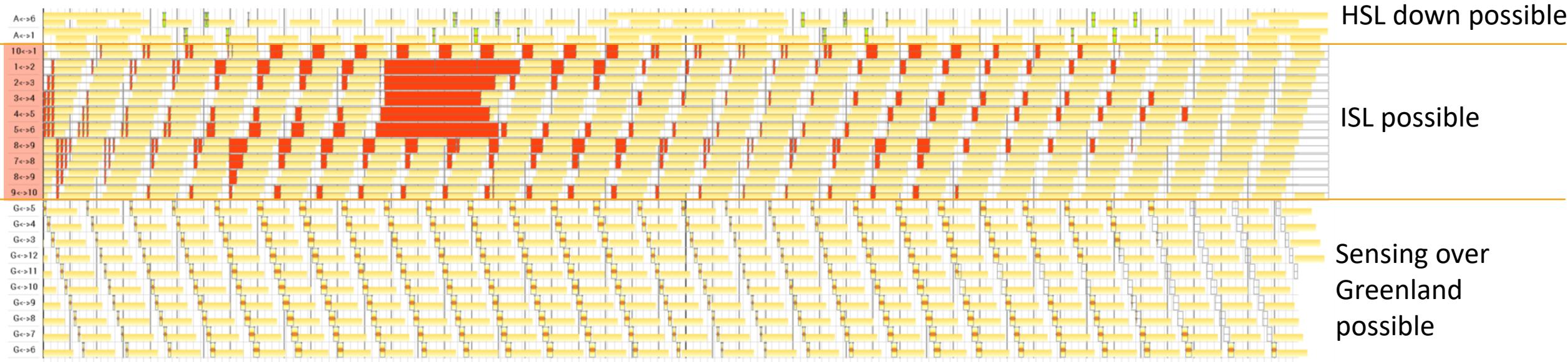
If each satellite has unlimited battery charge
but communication bound to end-to-end connection

7.9 MB delivered



Battery-Aware Contact Plan Design

When to communicate – based on **data flow and battery charge**



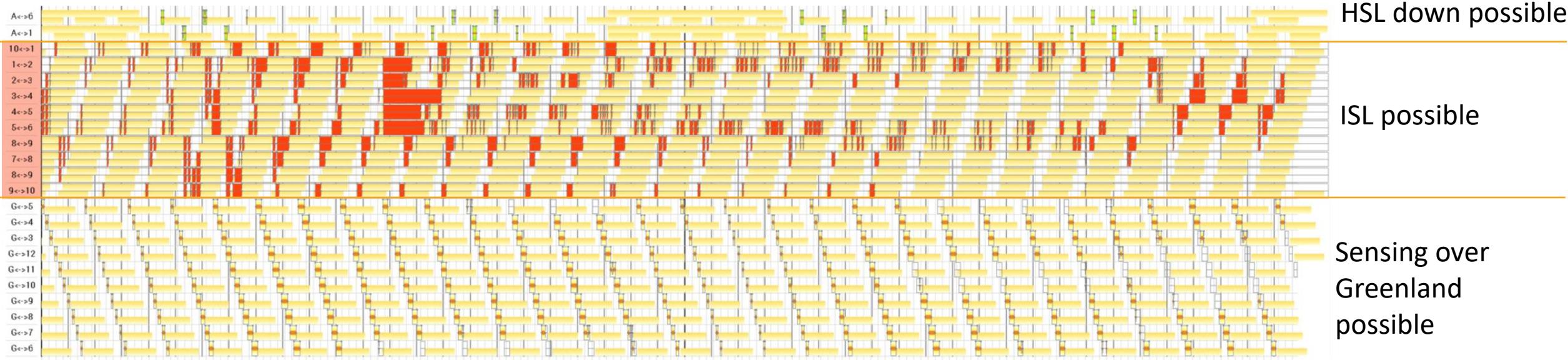
If each satellite has unlimited battery charge
and communication uses store-carry-and-forward

186.5 MB delivered



Battery-Aware Contact Plan Design

When to communicate – based on **data flow and battery charge**



If each satellite is bound to respect its battery charge
and communication uses store-carry-and-forward

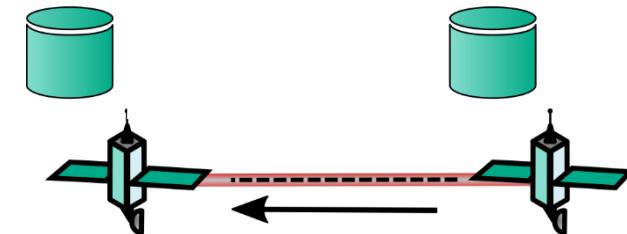
182.8 MB delivered



Under the Hood ③

Mixed Integer-Linear Programming

- Connection topology is treated piecewise static
- Discretisation is triggered by
 - Time elapse of t_{\max}
 - Topology changes
- Resulting problem and parameters are transformed into a MILP
- Optimal solution is a **contact plan maximizing data delivery**



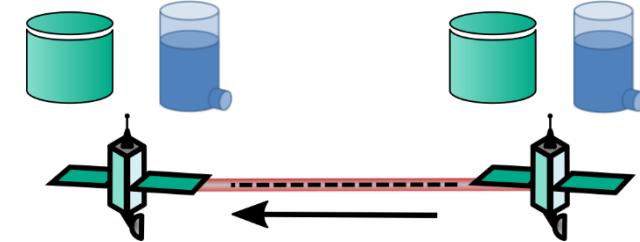
Data flow constraints
Transponder constraints
Buffer capacity constraints



Under the Hood ③

Mixed Integer-Linear Programming

- Connection topology is treated piecewise static
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 - which also includes a linear battery model per satellite
- Optimal solution is a **contact plan maximizing data delivery**



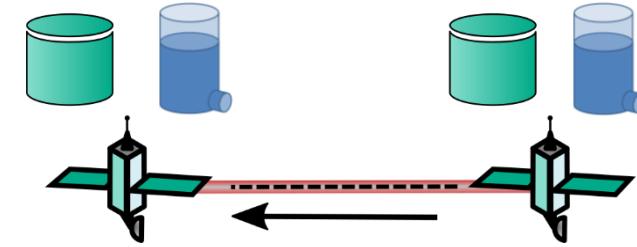
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- Optimal solution is a **contact plan maximizing data delivery while respecting battery constraints**



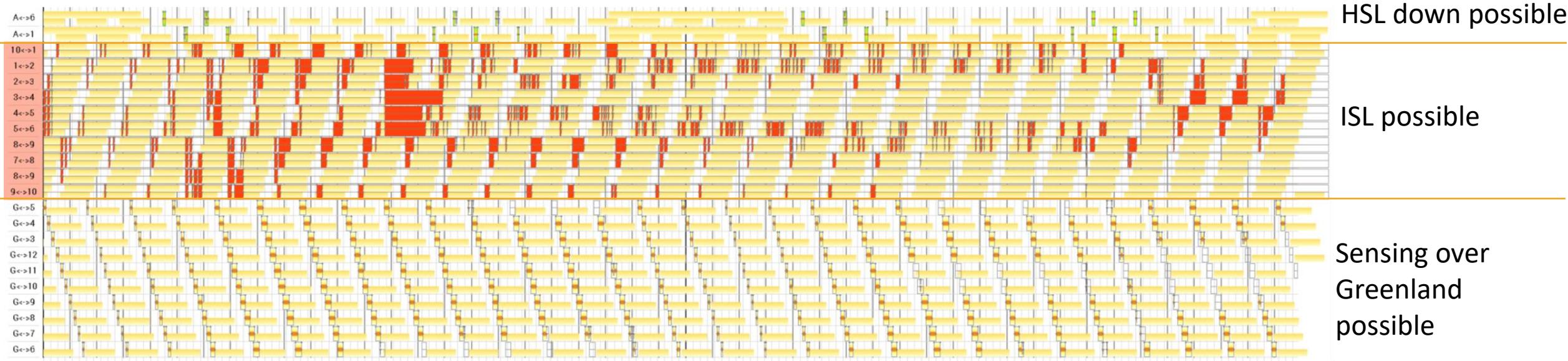
Data flow constraints
Transponder constraints
Buffer capacity constraints
Battery charge constraints



Battery-Aware Contact Plan Design

GLOBECOM 2018
IEEE TGCN 4(1)

When to communicate – based on **data flow and battery charge**



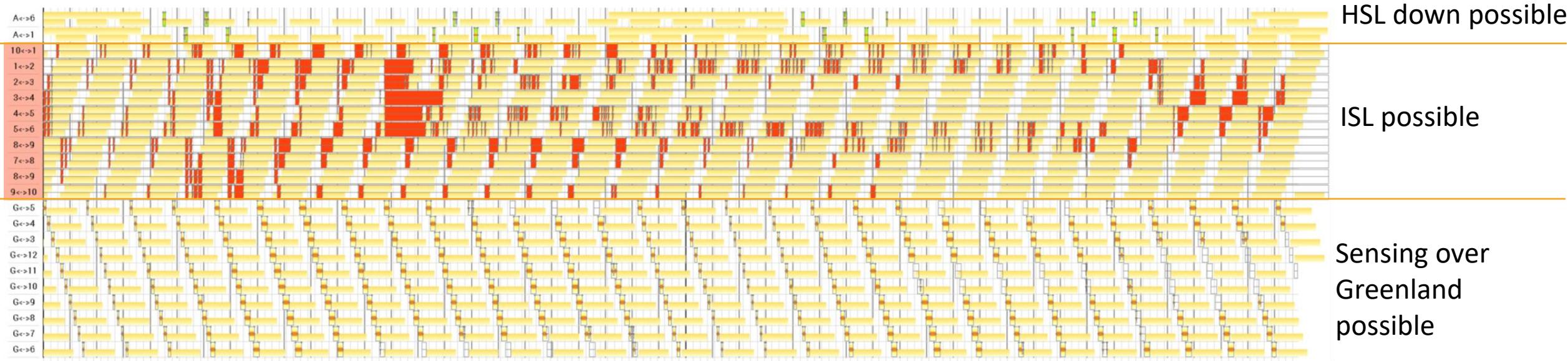
If each satellite is bound to respect its battery charge
and communication uses DTN

182.8 MB delivered



In-Orbit Demonstration?

When to communicate – based on **data flow and battery charge**



If each satellite is bound to respect its battery charge
and communication uses DTN

182.8 MB delivered



In-Orbit Demonstration?

We do not have ten satellites in orbit.

But we now have access to the GOMX-4 twins.

And there are plenty of related issues worth solving.

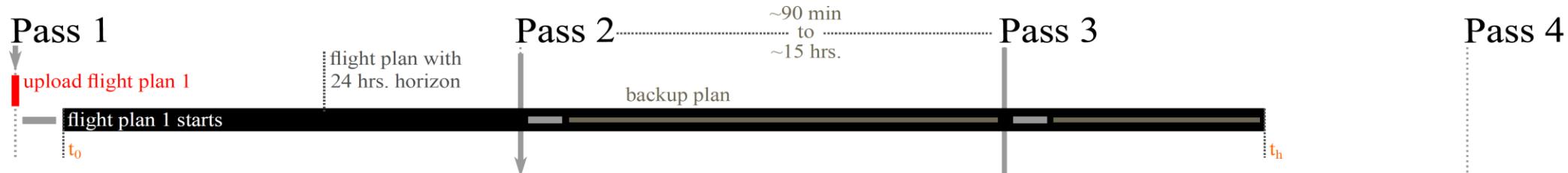
1. The scheduling horizon should not be a limit.
2. The battery model must not drift away from reality.

Ongoing
Work



Towards In-Orbit Experimentation

We are perpetuating the scheduling approach.



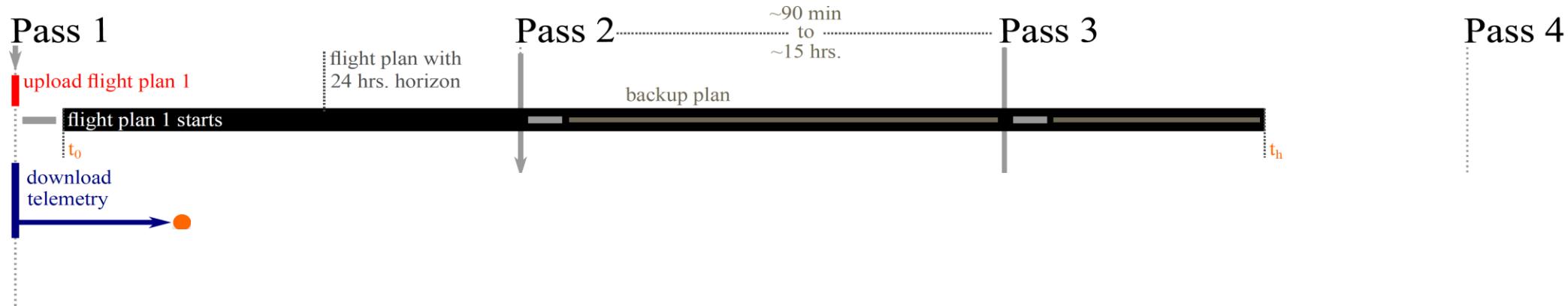
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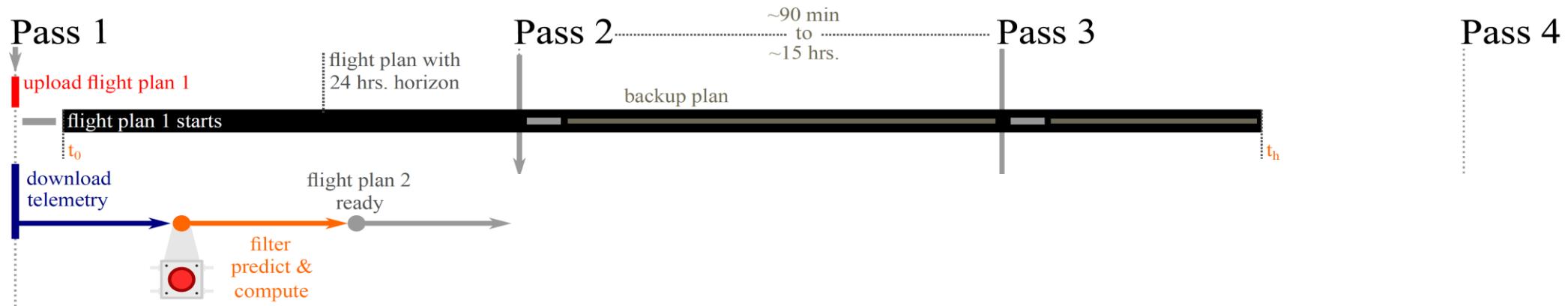
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Ongoing
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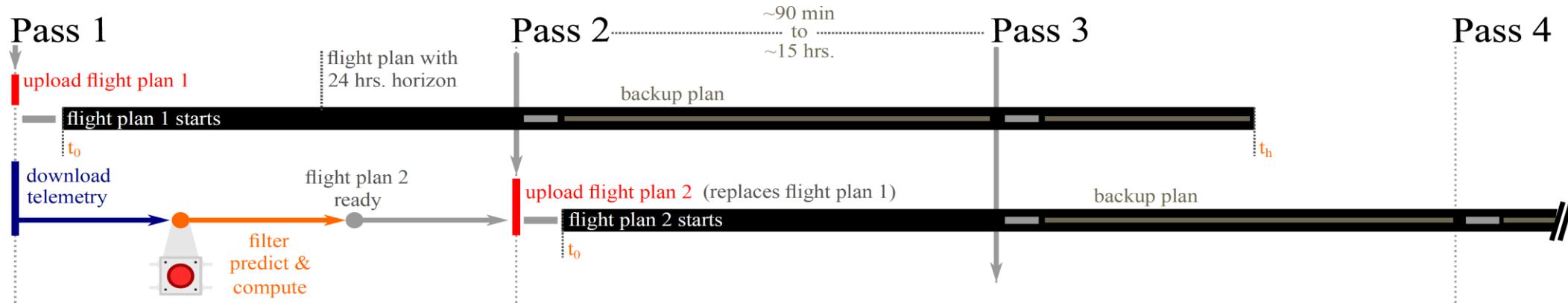
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Ongoing
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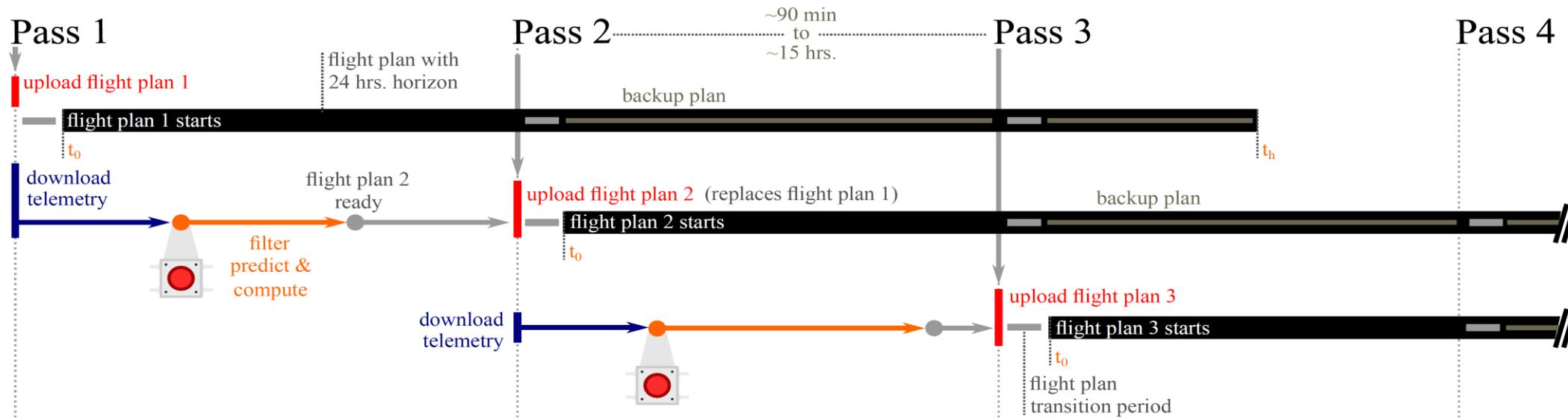
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Ongoing
Work



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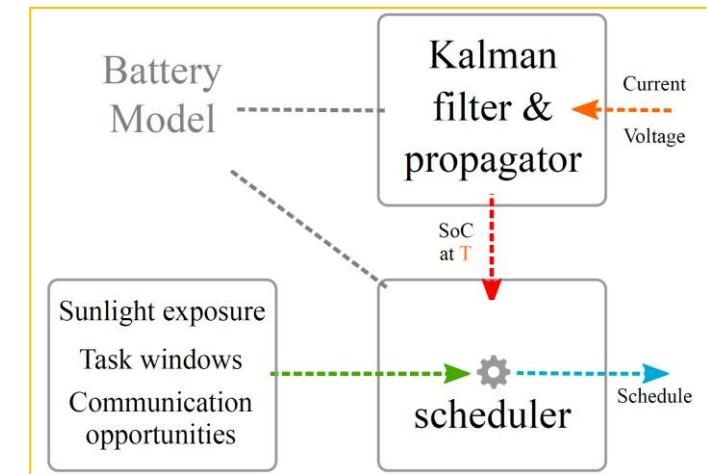
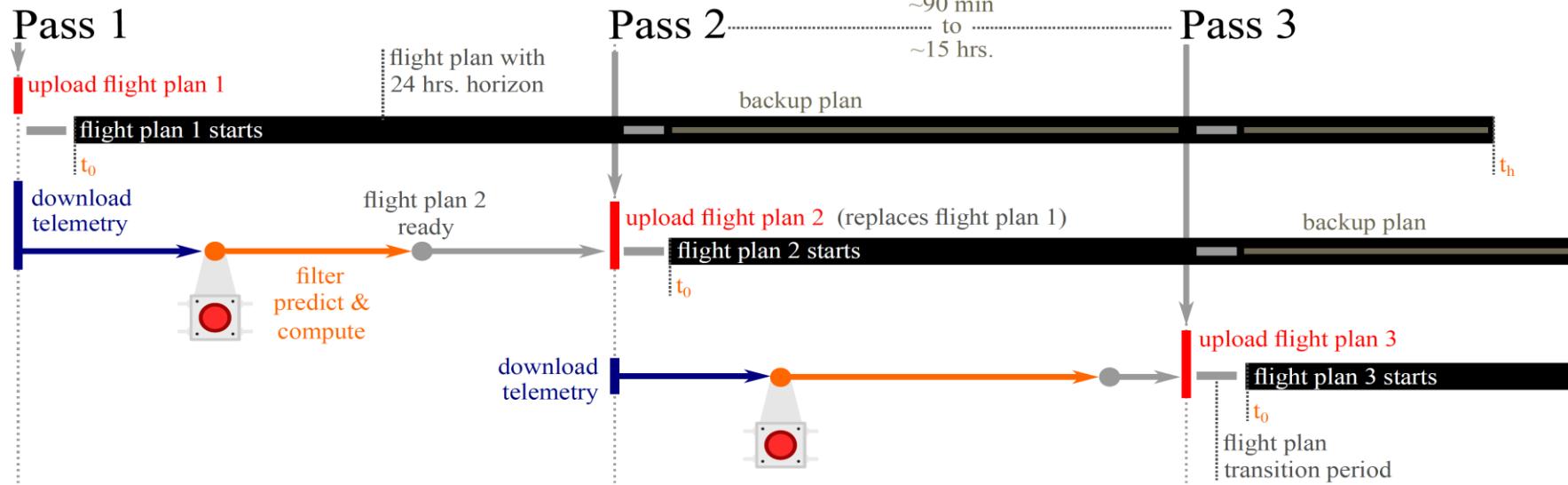
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Ongoing
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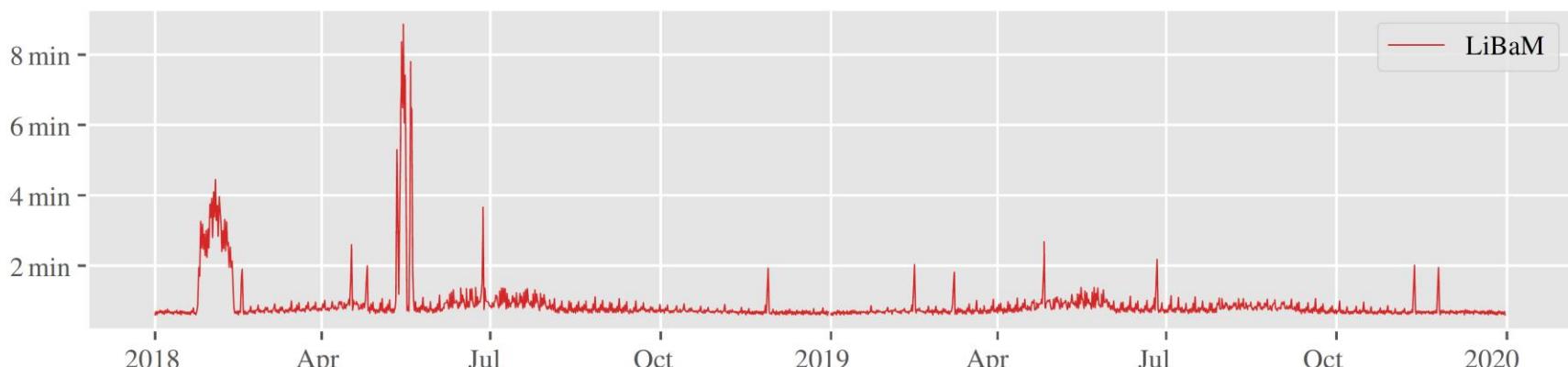
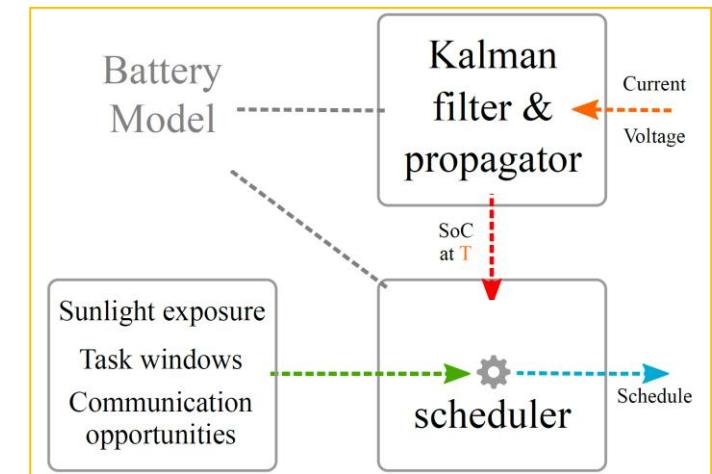
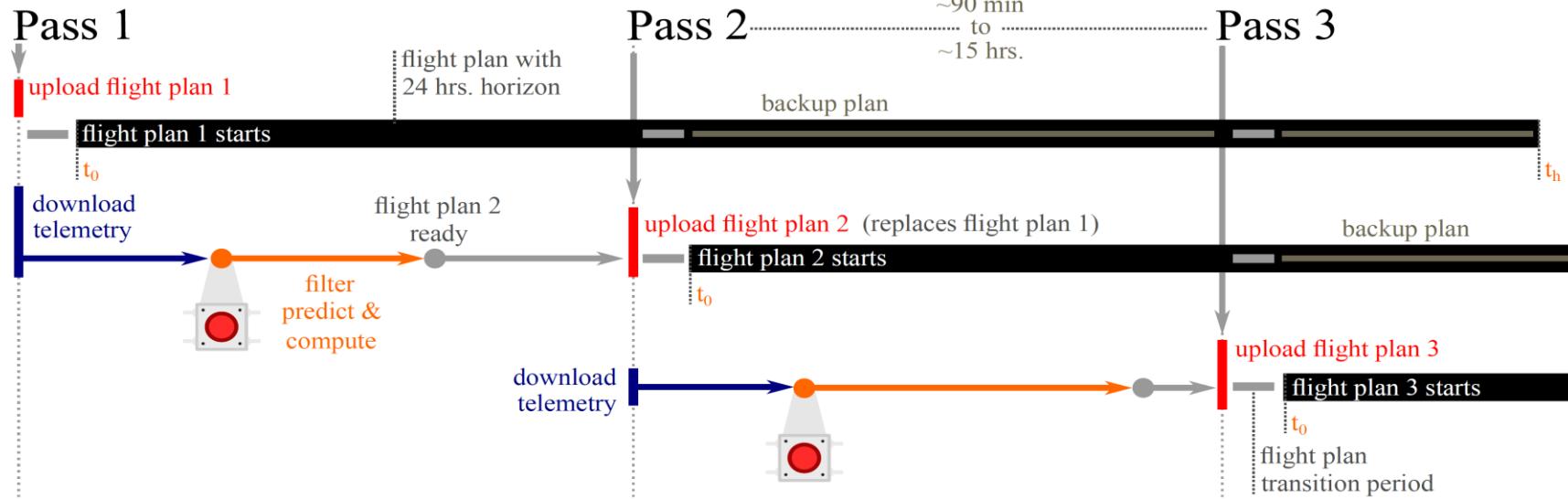
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Ongoing
Work



Towards In-Orbit Experimentation

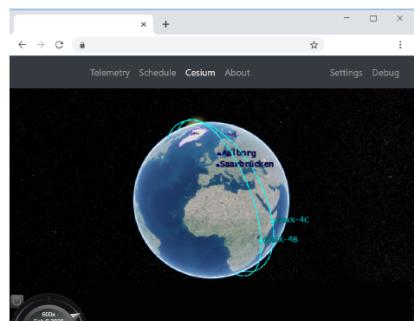
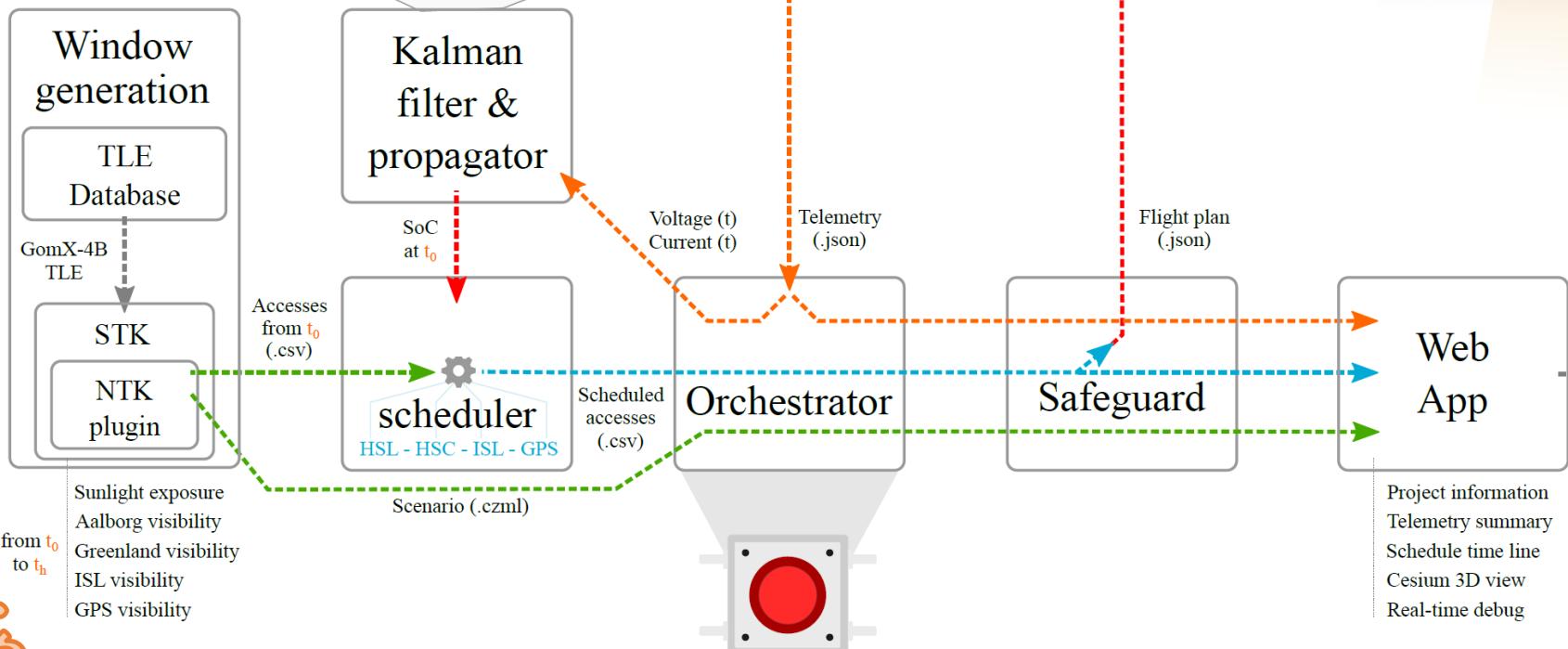
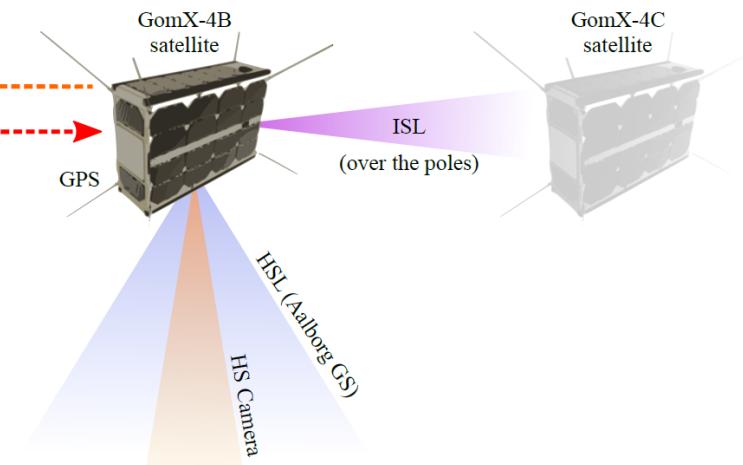
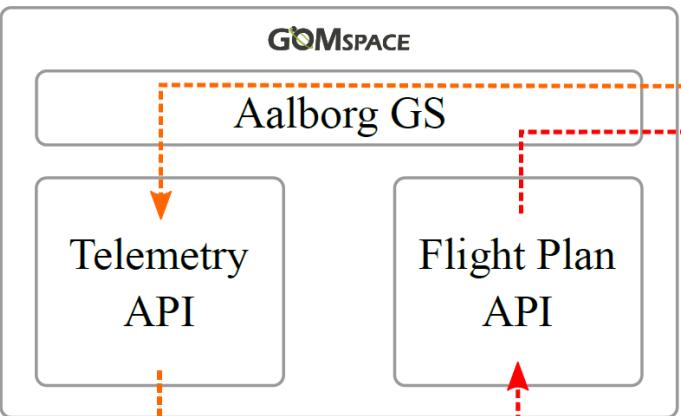
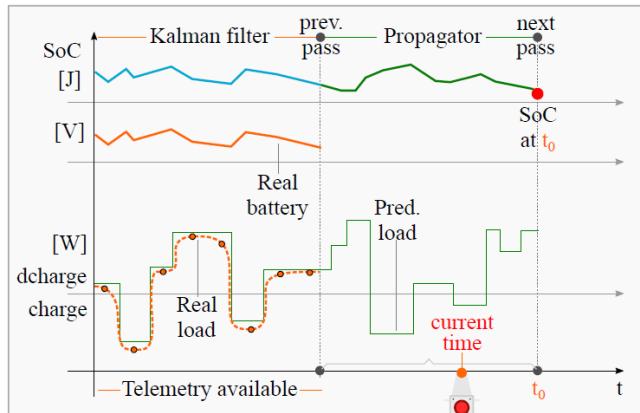
We are perpetuating the scheduling.



Ongoing
Work



Under the Hood ④



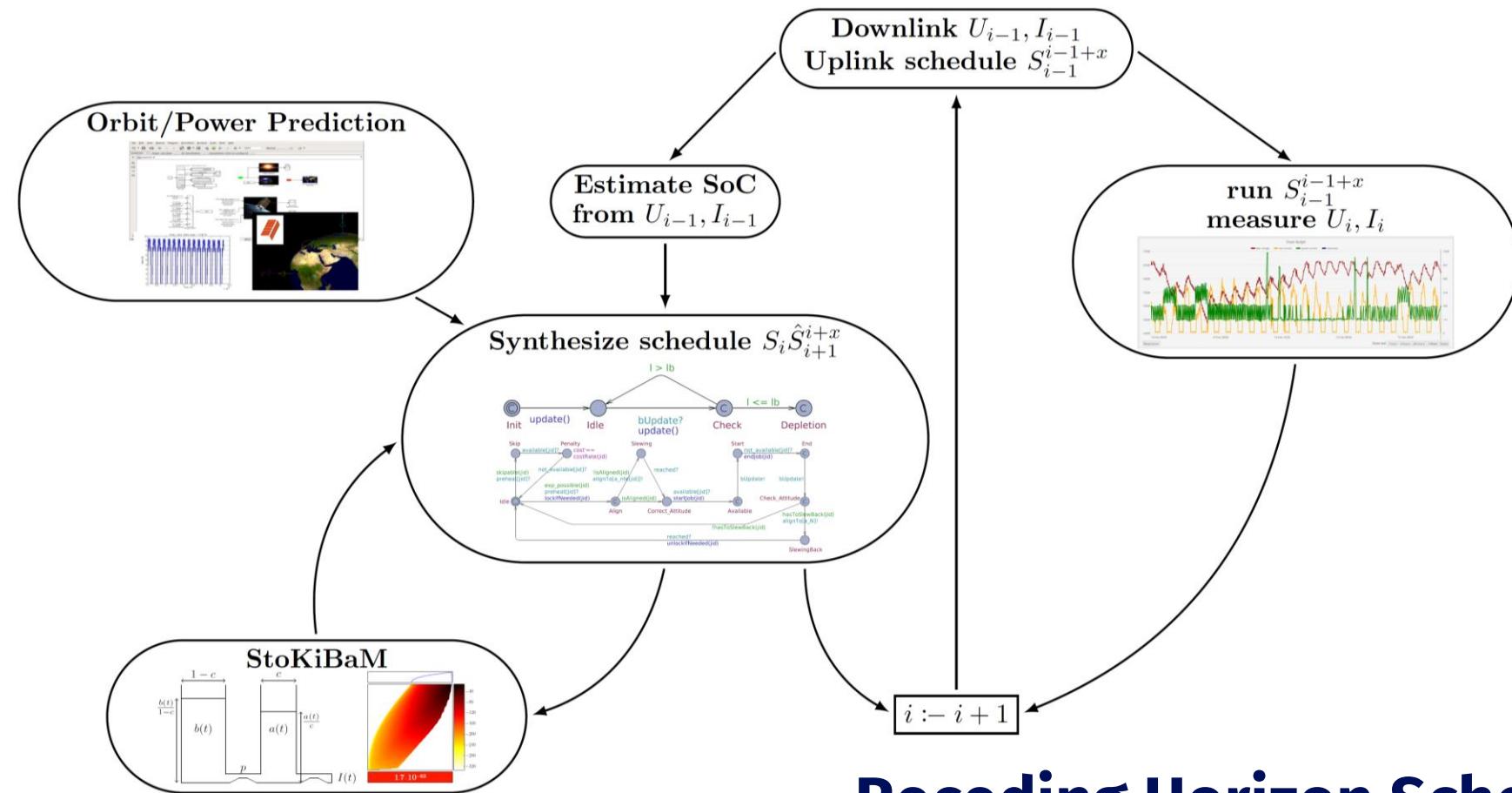
Project information
Telemetry summary
Schedule time line
Cesium 3D view
Real-time debug

Ongoing Work



Under the Hood ④

- Use in-orbit telemetry to improve state-of-charge estimations.
 - Produce new schedules while executing a schedule computed earlier.



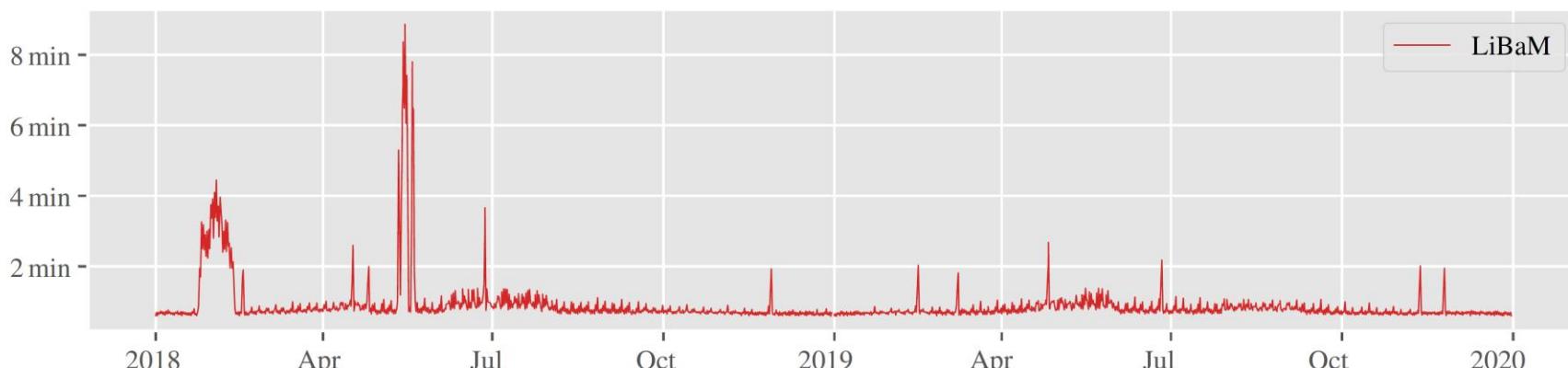
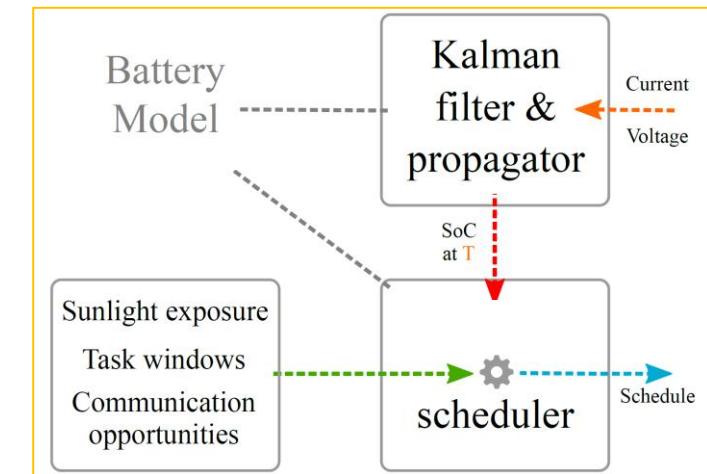
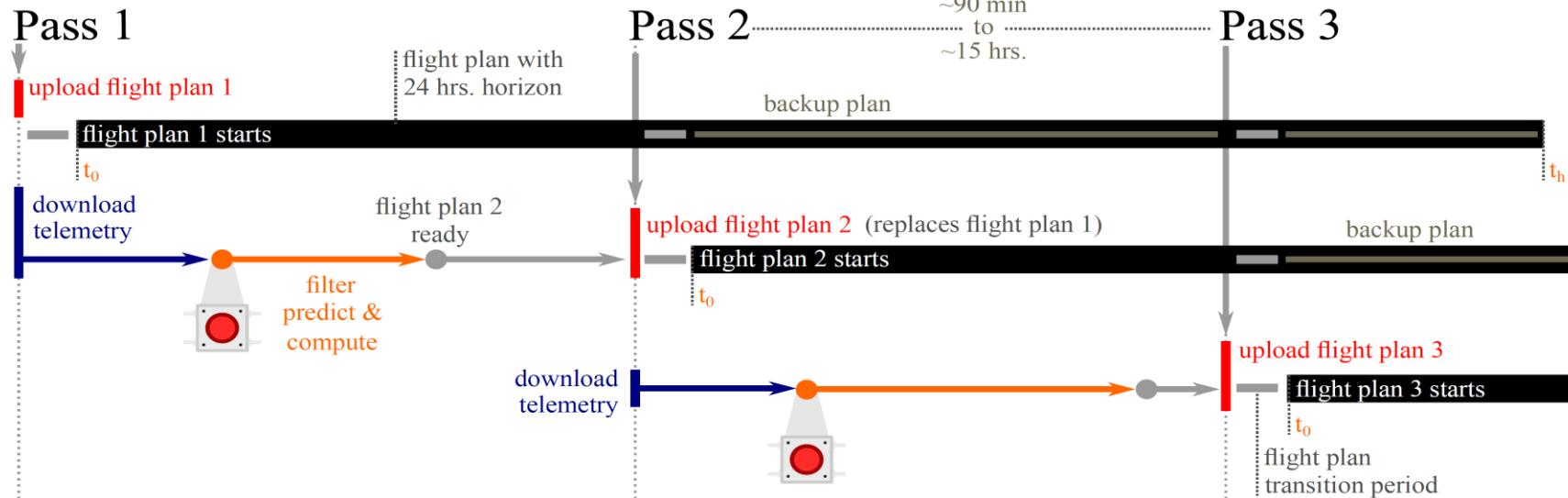
Ongoing Work

Receding Horizon Scheduling

Towards In-Orbit Experimentation

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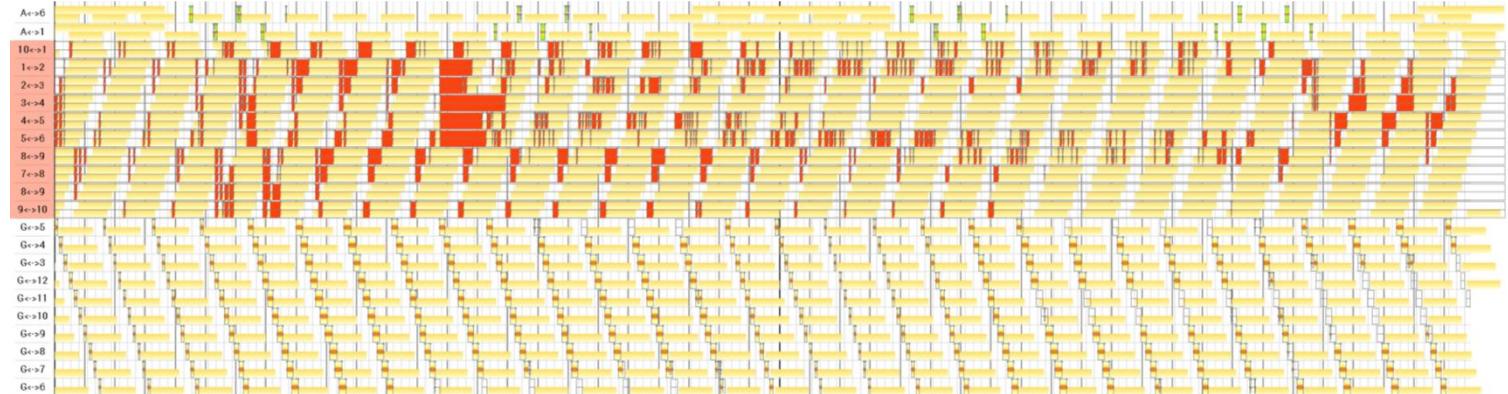
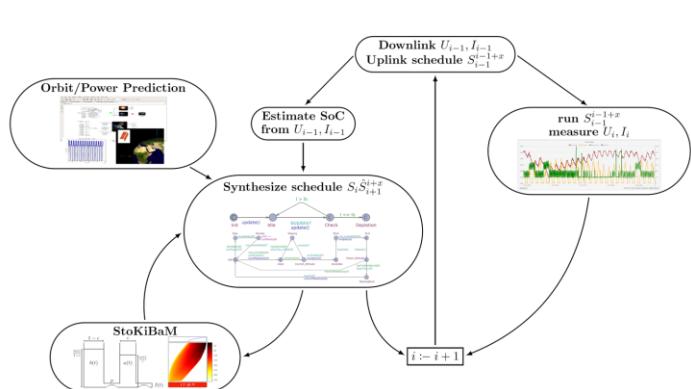
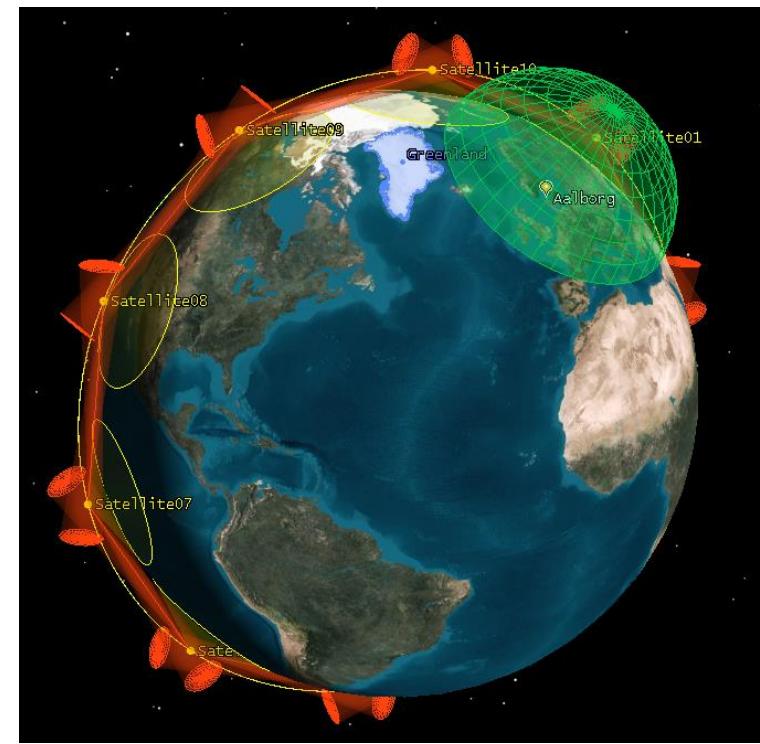
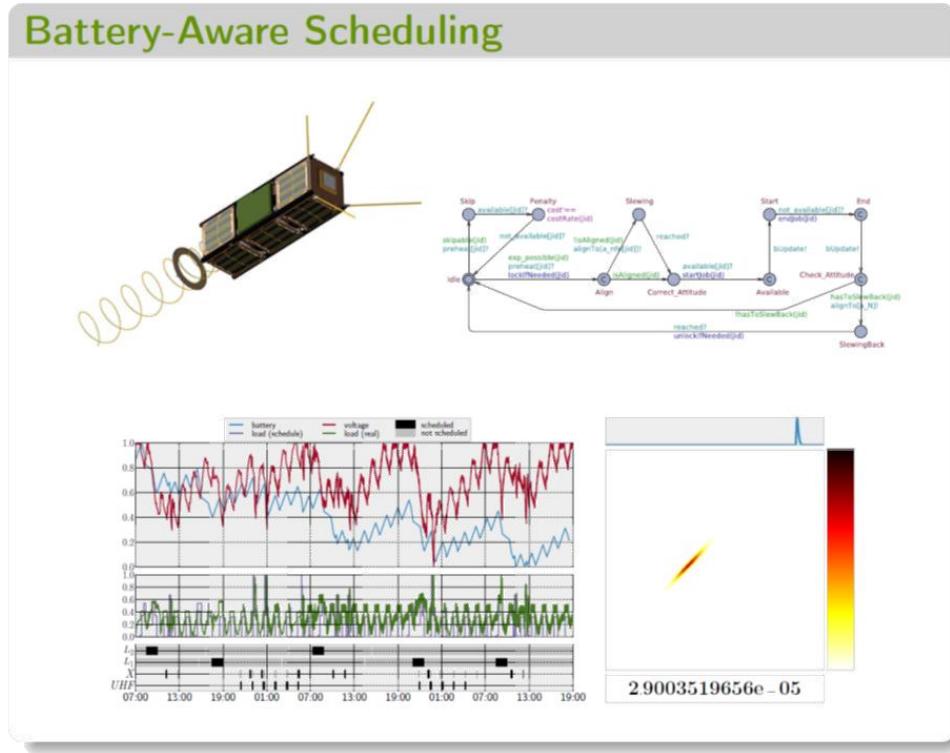
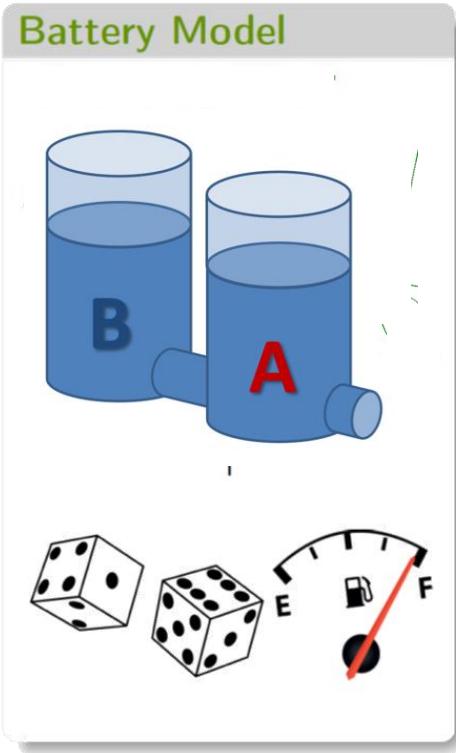
We are perpetuating the scheduling.



Ongoing Work



Conclusion



Conclusion

- The **power budgets** of small satellites are **very demanding**.
- We are investigating methods to **optimize resource usage** with respect to **data delivery and battery utilization**.
- The scheduling has been extended from single satellites to **optimal use of future small-satellite networks**.
- We are embarking on **in-orbit experiments** with GOMX-4A and B where **receding-horizon scheduling** and **continuous model learning** is put into the loop for **perpetuating the scheduling**.



Contributors

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Tilburg University

Boudewijn Haverkort



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