A Kernel for Energy-Neutral Real-Time Systems with Mixed Criticalities

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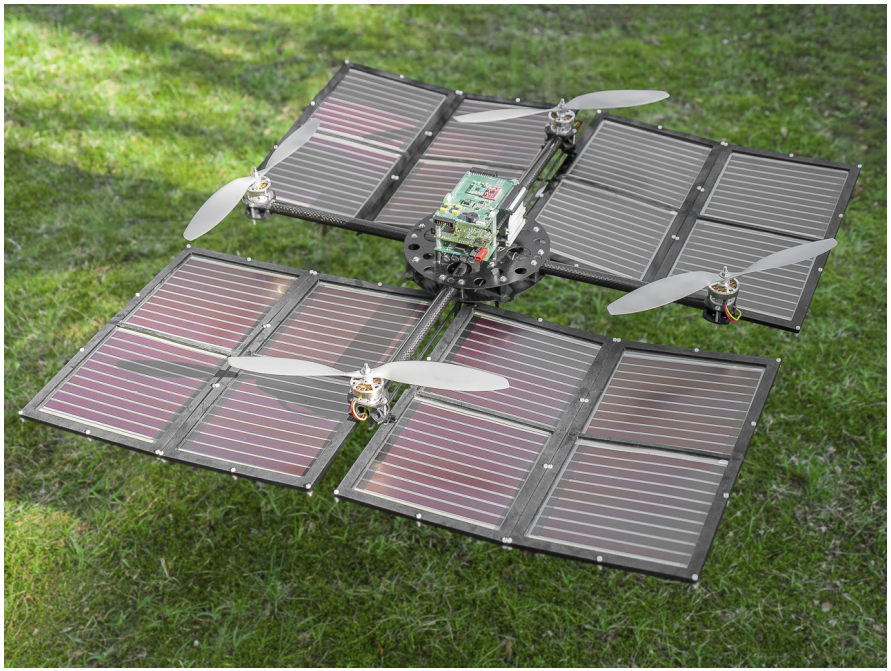
Application Scenario – Energy-Neutral Real-Time Systems

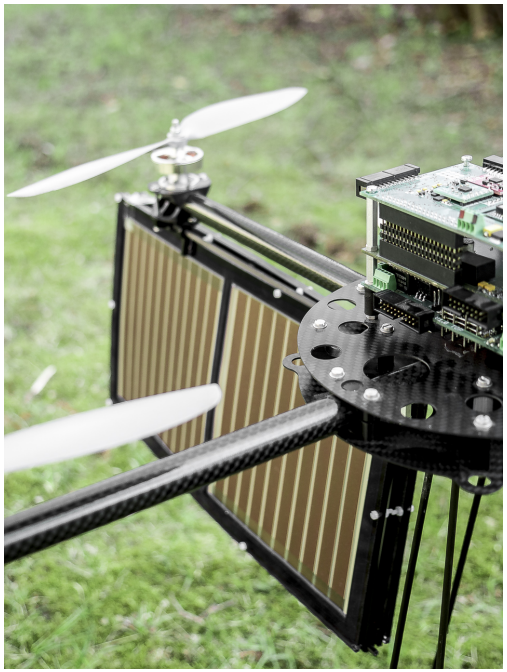
Energy-Neutral Real-Time Systems

- Energy-neutral prototype of the I4Copter[1]
- Main modes: flying, landed/harvesting

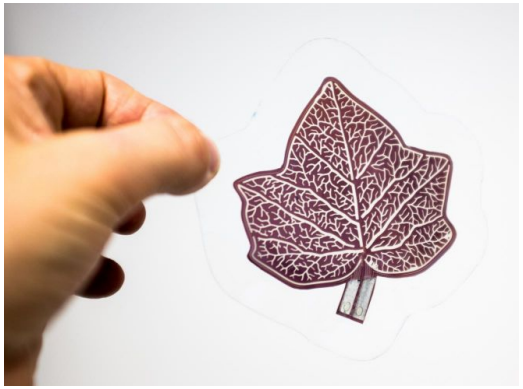
[1] Ulbrich et al. *I4Copter: An Adaptable and Modular Quadrotor Platform*, SAC'11

Application Scenario – Energy-Neutral Real-Time Systems



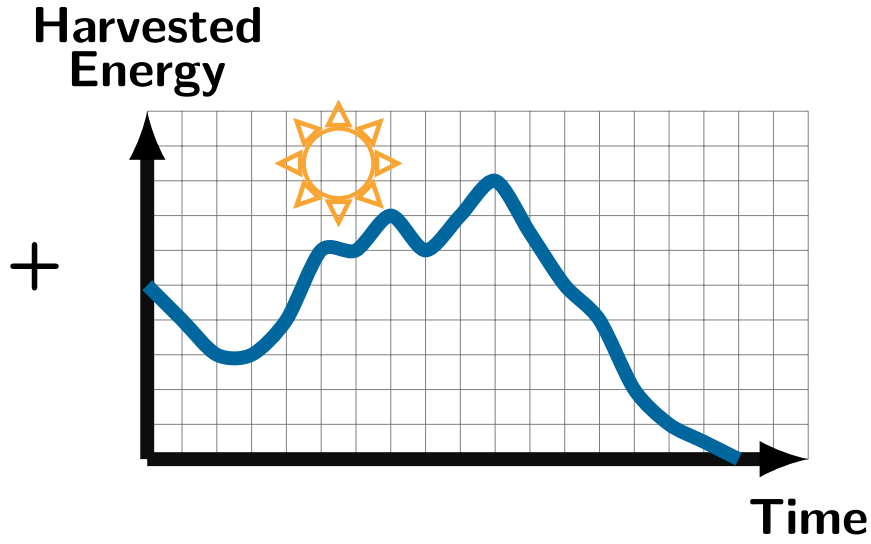


- Expand panels for charging
- Collapse panels during flight
- Lightweight, robust solar films



organic solar films: Belectric OPV, `solarte.de`

Problems – Energy-Neutral Real-Time Systems

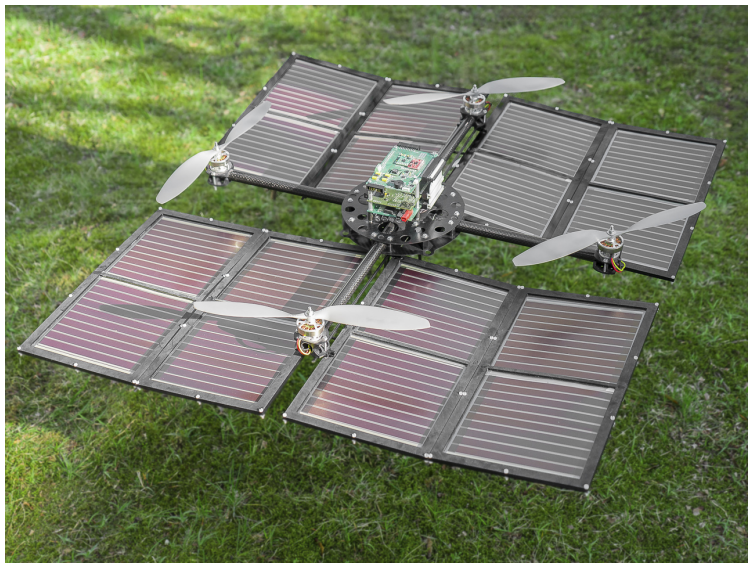


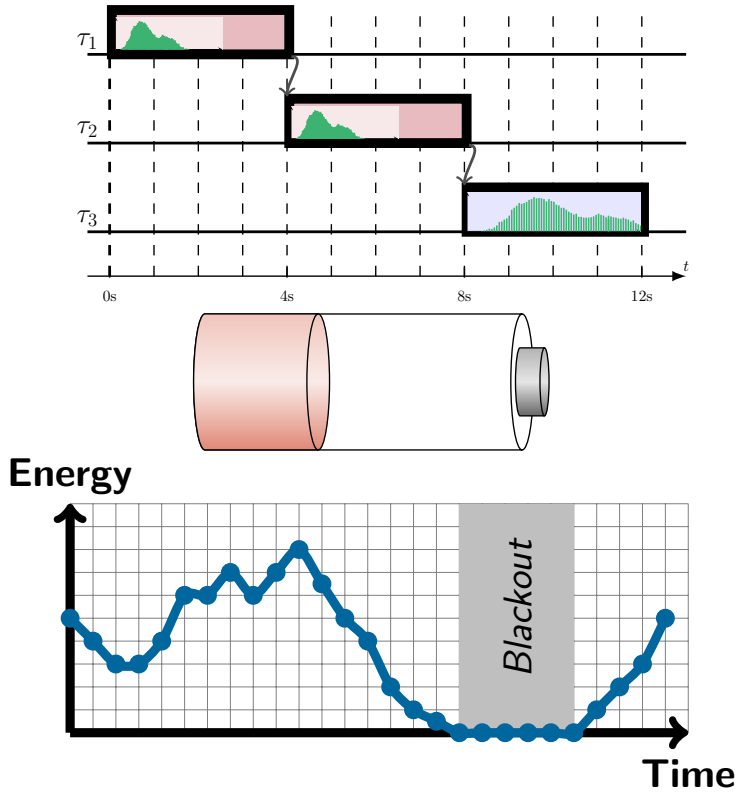
Real-Time Systems under Hard Energy Constraints

- Guarantee **timeliness**: position/flight control
- Respect **energy constraints**: limited/replenishable storage

  ☞ *Energy surpasses timeliness and vice versa*

Energy-Neutral Real-Time Systems – Challenges

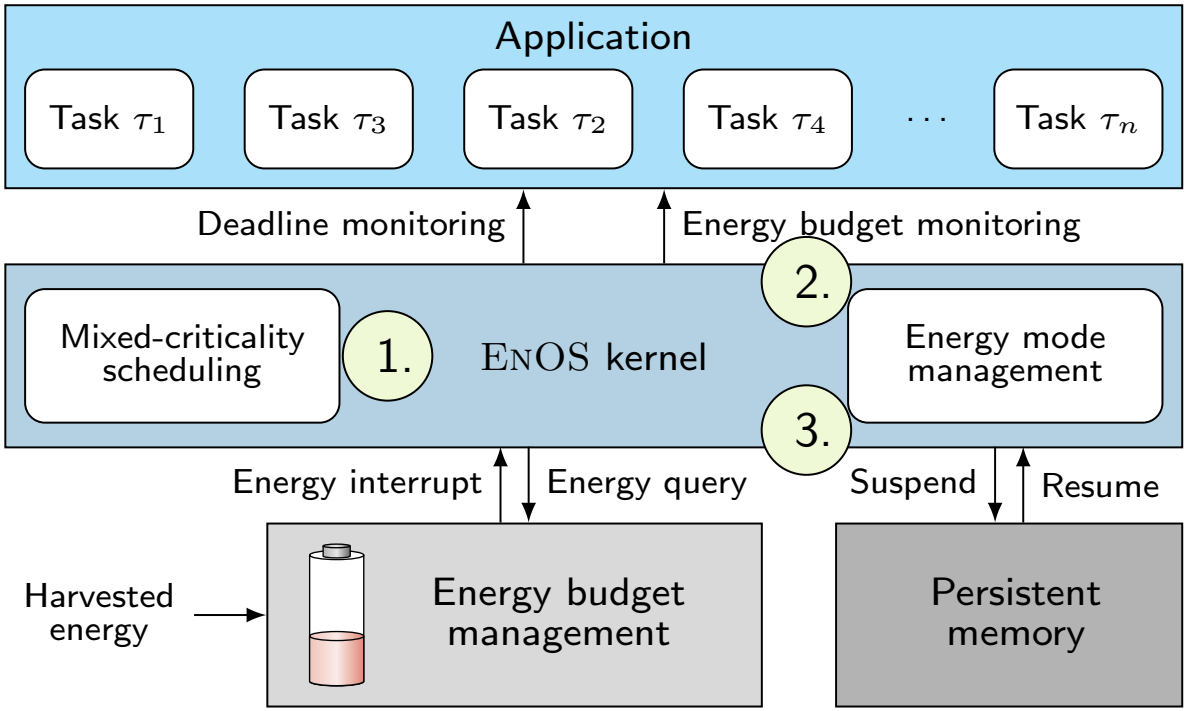




Challenges of Energy-Neutral Real-Time Systems

1. **Scheduling**: mixed constraints (time & energy), mixed criticalities
2. **Energy monitoring**: consumed & available energy budgets
3. **Consistency**: survive blackout periods

The EnOS Kernel

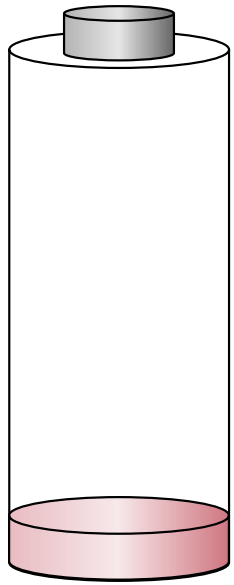


The EnOS Kernel

1. **Scheduling** with mixed criticalities and mixed constraints
2. Energy-budget **monitoring**
3. Surviving **blackouts** (suspend and resume)

Outline

1. Motivation
2. Scheduling with Mixed Criticalities & Mixed Constraints
3. Energy-Budget Monitoring
4. Surviving Blackouts
5. Evaluation
6. Conclusion

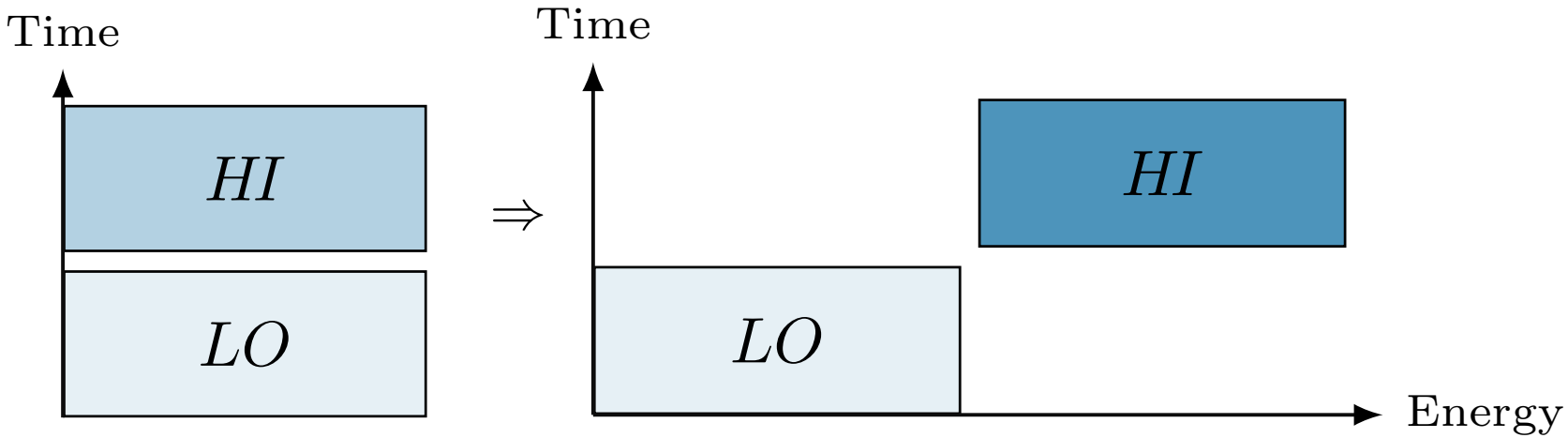


Motivation – Mixed-Criticality Systems

Guarantees $\rightsquigarrow$ Pessimism $\rightsquigarrow$ Slack Time

- "Flight critical" : inertial measurement/control $\Rightarrow C(HI)$
- "Mission critical": capturing images $\Rightarrow C(LO)$
- **Hard guarantees** for **high time criticality** tasks
- **More critical** task $\Rightarrow$ **more pessimistic** WCET estimate
- **Redistribute** resources from LO to HI (preempt LO)

Energy-Constrained Mixed-Criticality Systems

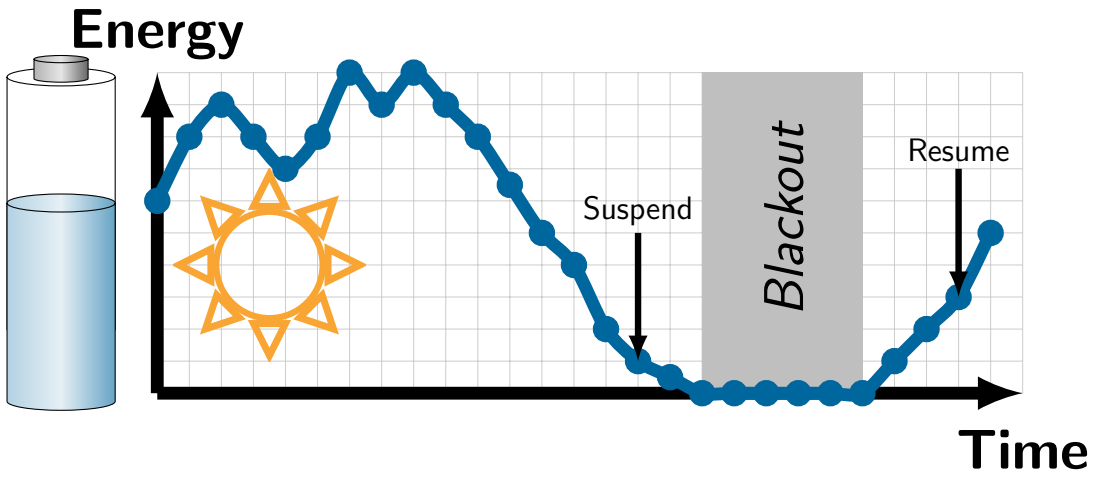


- **Völp et al.** *Has Energy Surpassed Timeliness?*
  Scheduling Energy-Constrained Mixed-Criticality Systems, RTAS'14
- **Mixed constraints**: energy & time
- Approach (EA-OCBP) considers
  - $C(LO), \ldots, C(HI)$, and $E(LO), \ldots, E(HI)$
  - Hyperperiod energy budget: E^{HP}
- **More pessimistic WCET** $C \rightsquigarrow$ **more pessimistic WCEC** E[1]

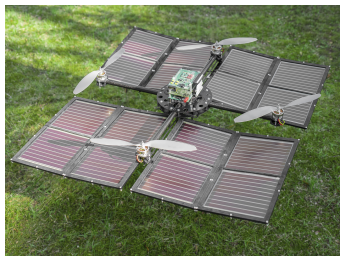
☞ **Coupling** of time and energy constraints

[1] worst-case energy-consumption (WCEC)

Time Criticality versus Energy Criticality



VS.



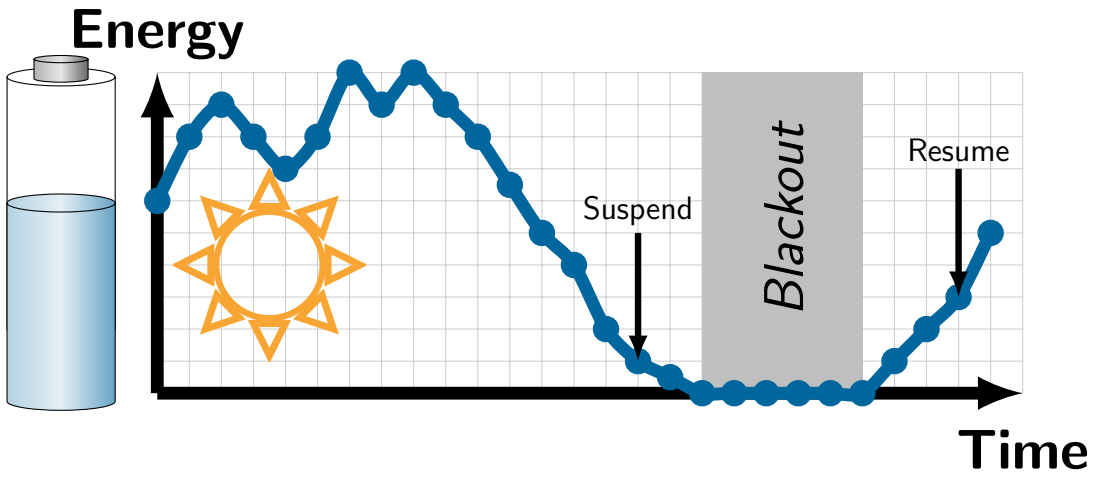
When is **timeliness** most critical?

- During **activity phases** (i.e., flight mode)
- Uncritical in suspension phase
  - ☞ No time guarantees across blackout periods

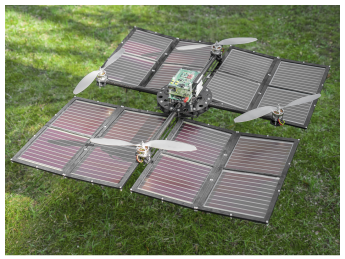
When are **energy constraints** most critical?

- **Close to inactivity phases** (i.e., depletion)
- Safe suspension to persistent memory

Time Criticality versus Energy Criticality



VS.



When is **timeliness** most critical?

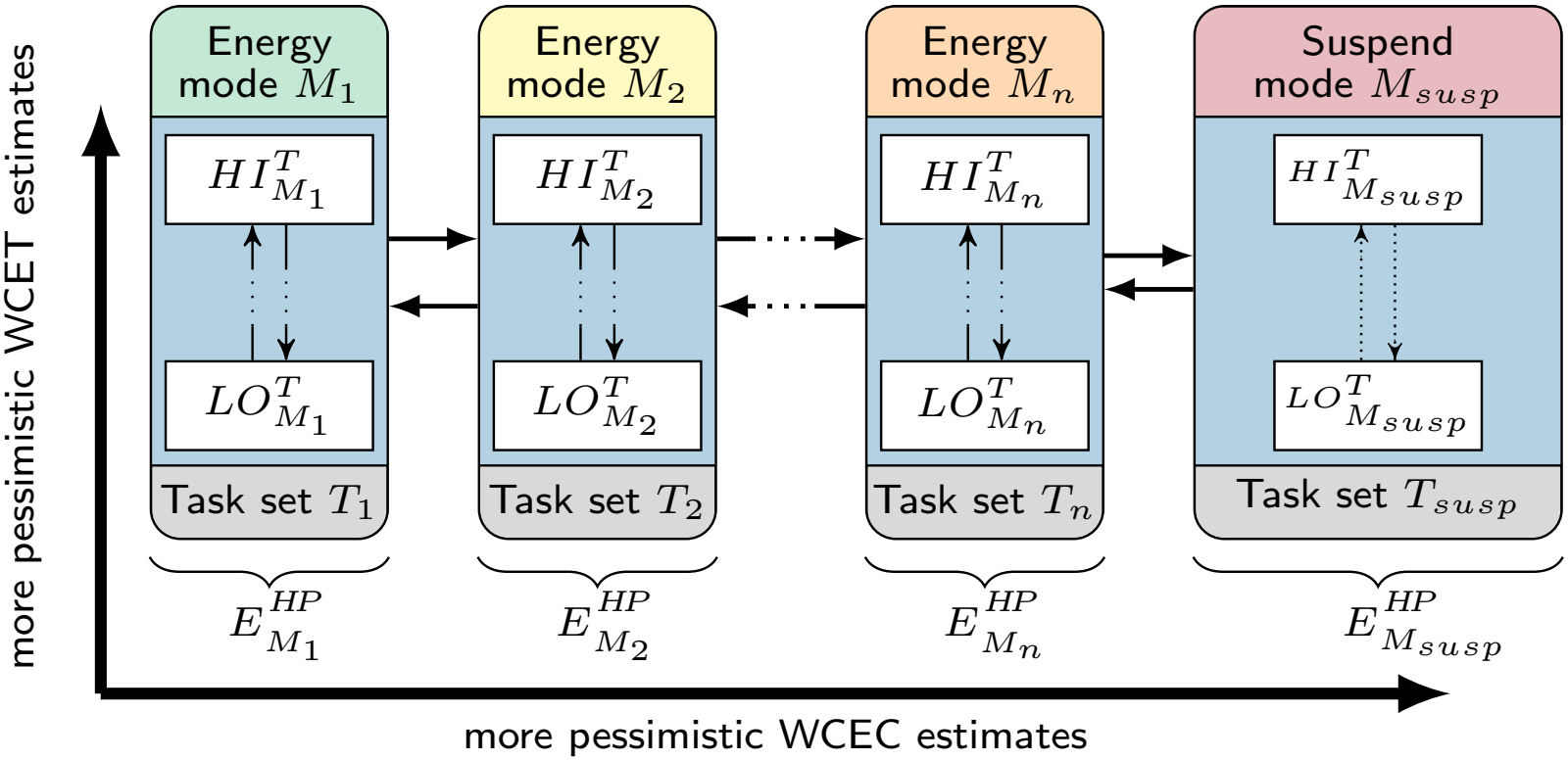
Time vs. Energy Criticality

1. Energy is critical
2. Time is critical
3. *... but not necessarily at the same time*

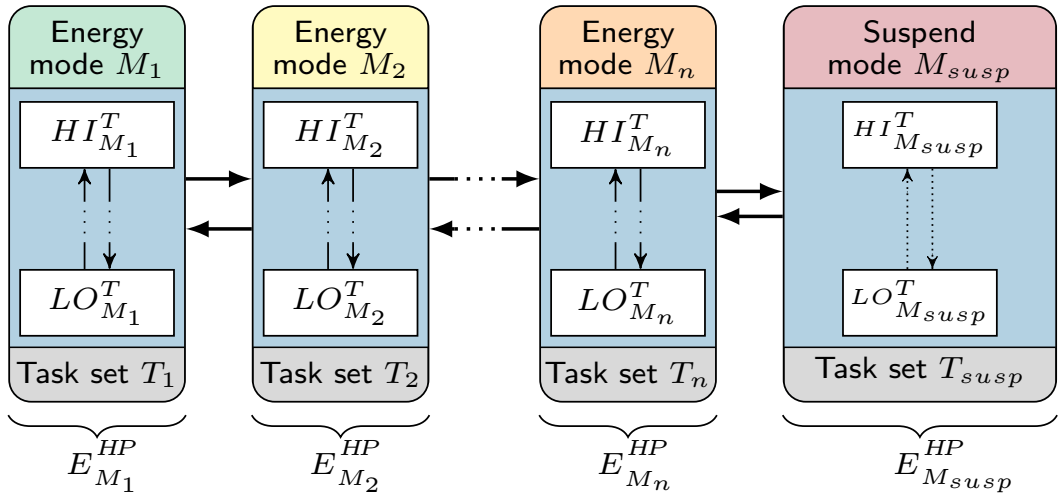
   ☞ **Decoupling** of time and energy into **distinct energy modes**

- Safe suspension to persistent memory

Energy-Criticality Modes & Time-Criticality Levels



Energy-Criticality Modes & Time-Criticality Levels



Multi-Mode Model

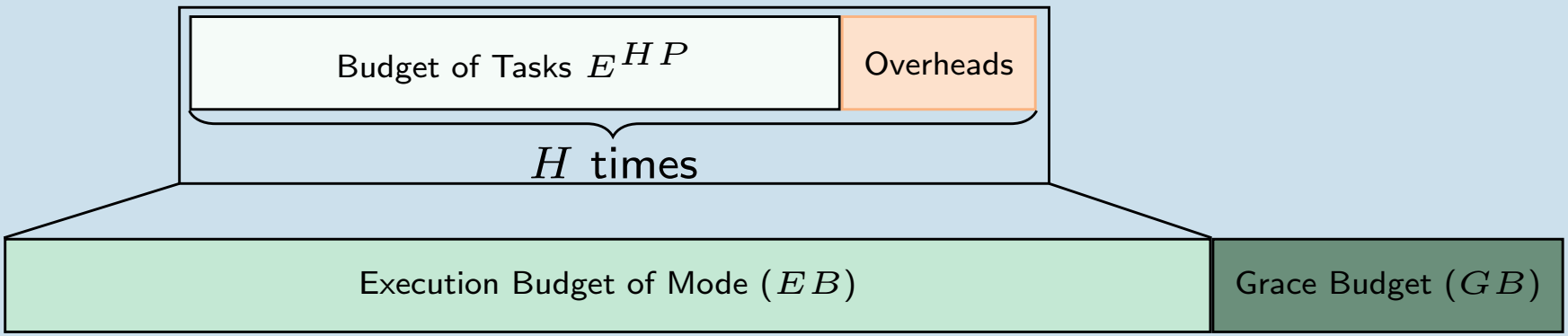
- Time (criticality) *levels* & energy (criticality) *modes*
- Energy budget for hyperperiod: $E^{HP}_{M_i}$
- **Different functionality** (task set) per mode possible
- **Less pessimistic WCEC analyses** in less critical energy modes
- Full functionality when energy plentiful

  ☞ **Decoupling** energy and time criticalities

Scheduling – Offline Part

- Task model: periodic, implicit deadlines, independent tasks, mixed criticality & mixed constraints: LO^T, HI^T, LO^E, HI^E
- Static priority assignment (using EA-OCBP)

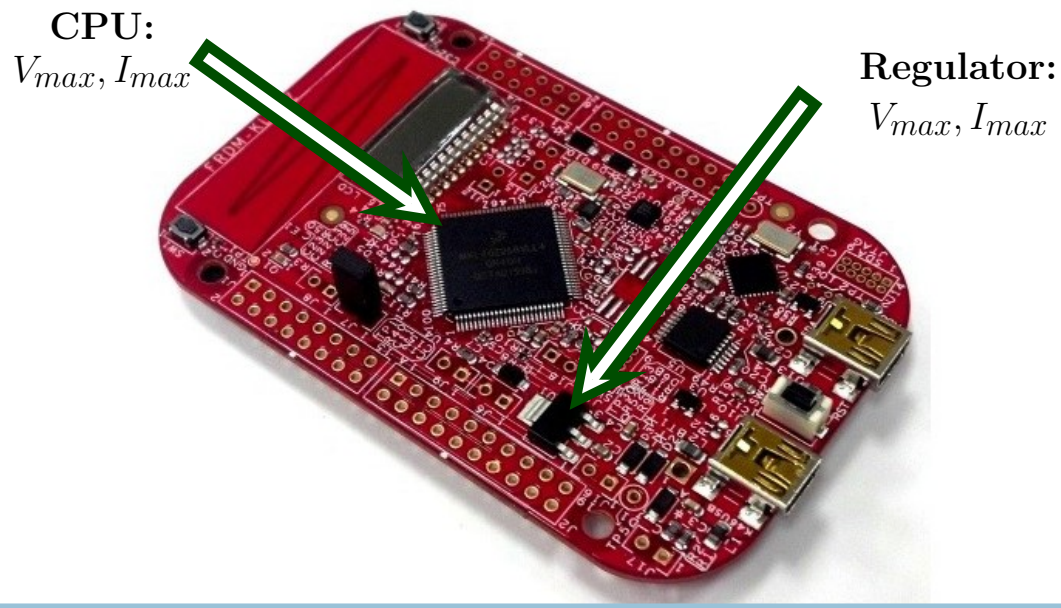
Energy-Budget Composition on Mode M_i



- **Execution budget** EB: estimate *depending on mode*
  - Stay on mode for *configurable number of hyperperiods* (H)
- **Grace budget** GB: handle budget violation in hyperperiod
  - *Ensures finishing hyperperiod*

  ☞ Enable **safe mode switches**

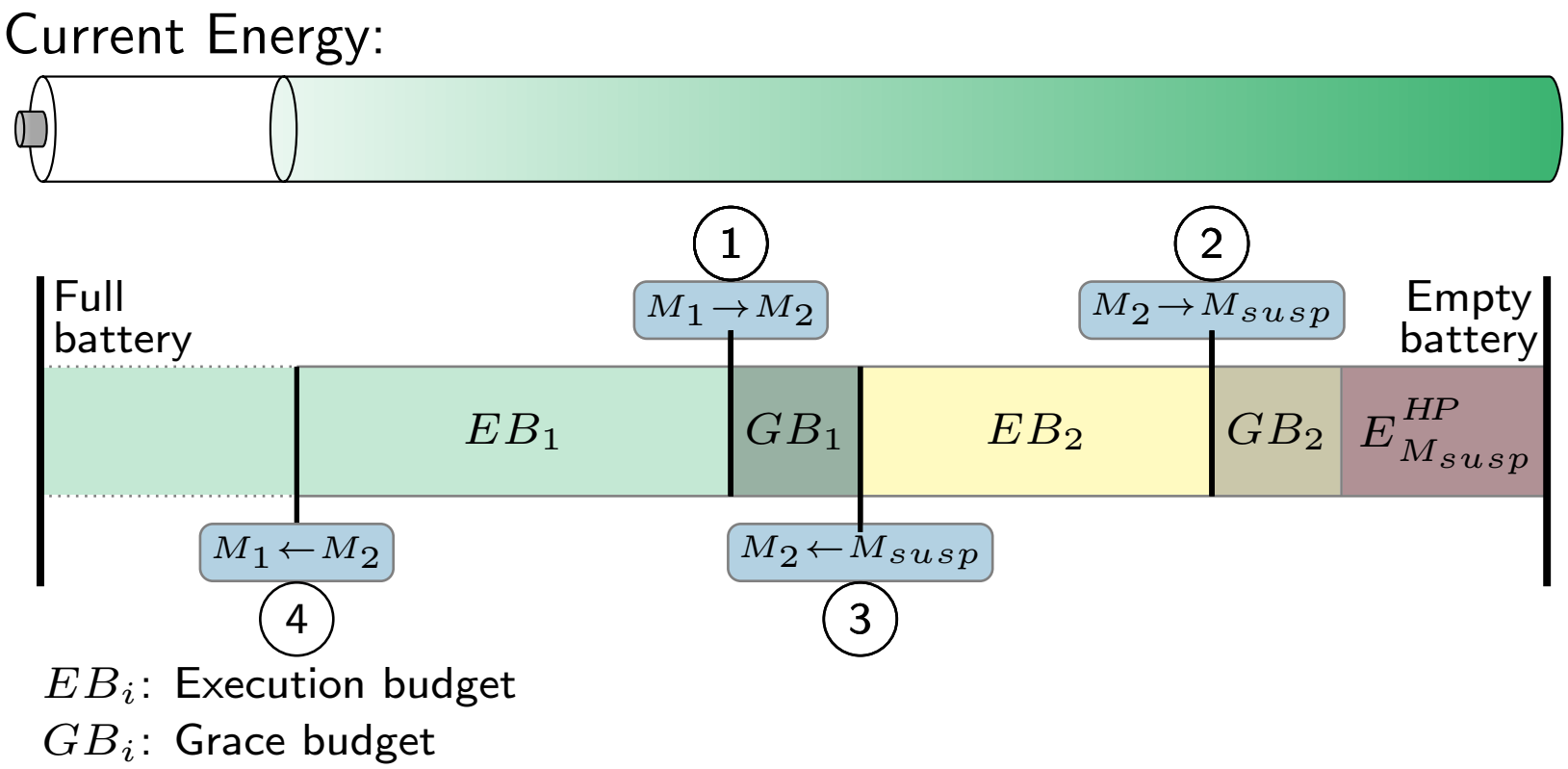
Scheduling – Offline Part – Grace Budget



How to get **safe upper bound** on Hyperperiod's WCEC?

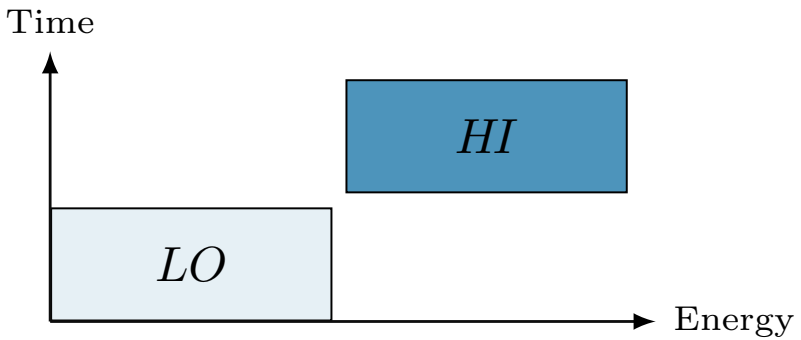
- WCEC of lowest energy-criticality mode is optimistic, not safe
- Trick exploits
  - **Fixed duration** of hyperperiod HP_{M_i}
  - **Physical upper limits** of electronic components
  - $E_{grace} = P_{max} \cdot HP_{M_i}$
    ☞ **Very pessimistic, but safe** (required once per mode)

Scheduling – Online Part

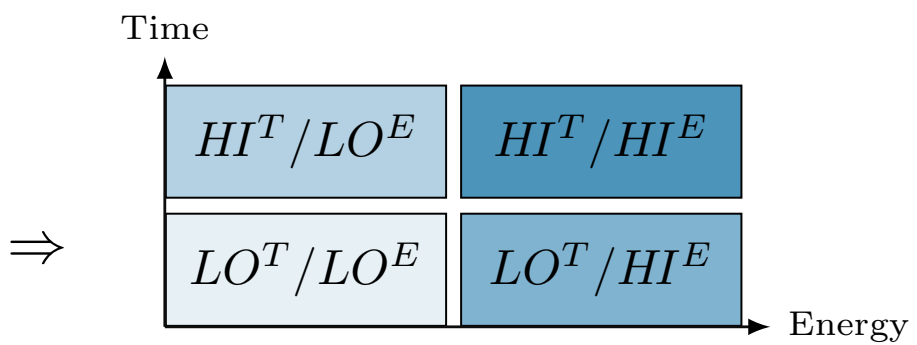


- **Monitoring energy budgets** of modes M_i
- Mode switches based on available and offline determined budgets
- Grace budget for **safe degradation**: allow finishing hyperperiod

Scheduling Enhancement



EA-OCBP Approach



Multi-Mode Model of EnOS

Enhancement

- Avoid pessimism when energy is plentiful

  ☞ **Full decoupling** of WCET and WCEC ✓

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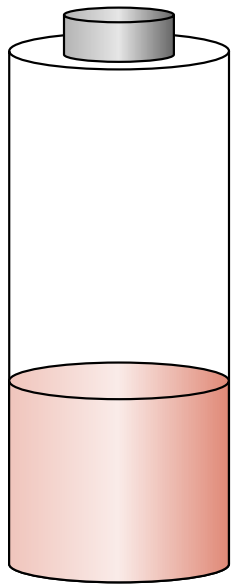
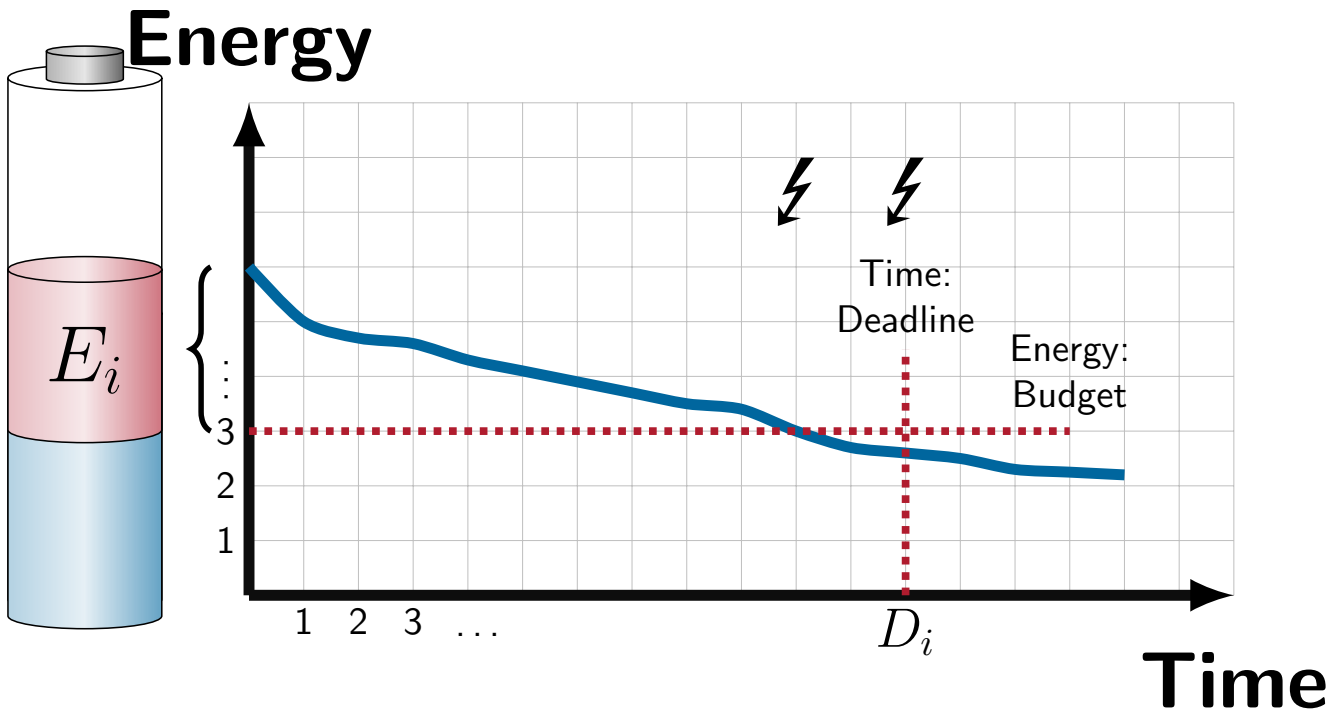


Deadline vs. Energy-Budget Violations



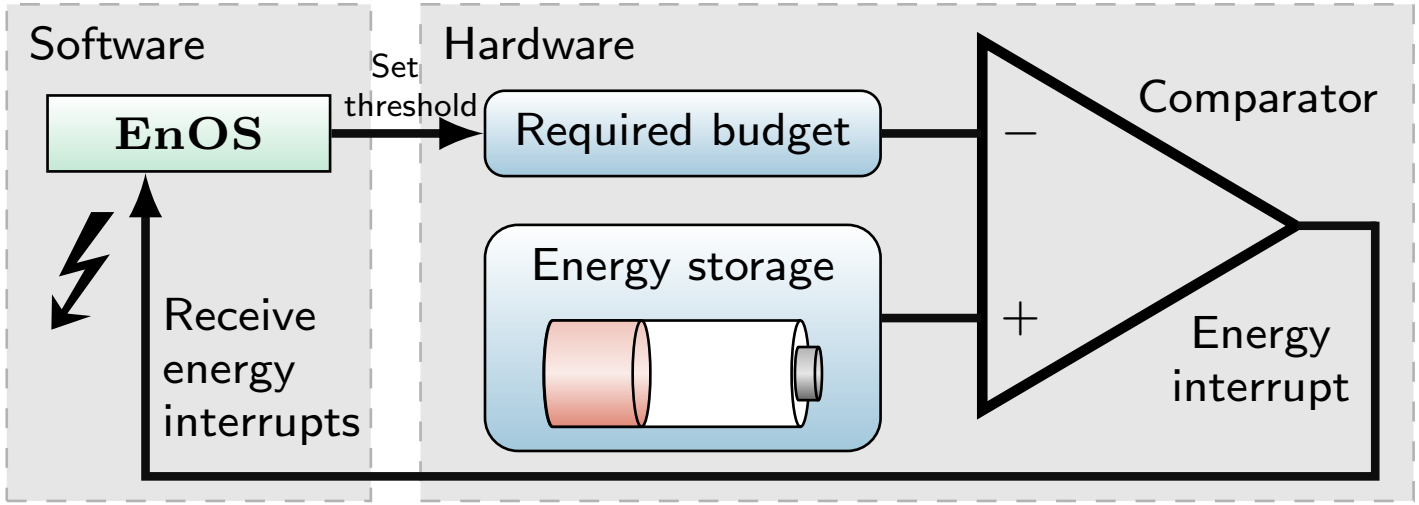
How to detect **energy-budget violations**?

✓ Detecting deadline violations

- Hardware operates timing-oriented
- General-purpose timers

✗ Detect energy-budget violations

Energy-Budget Monitoring – Concept

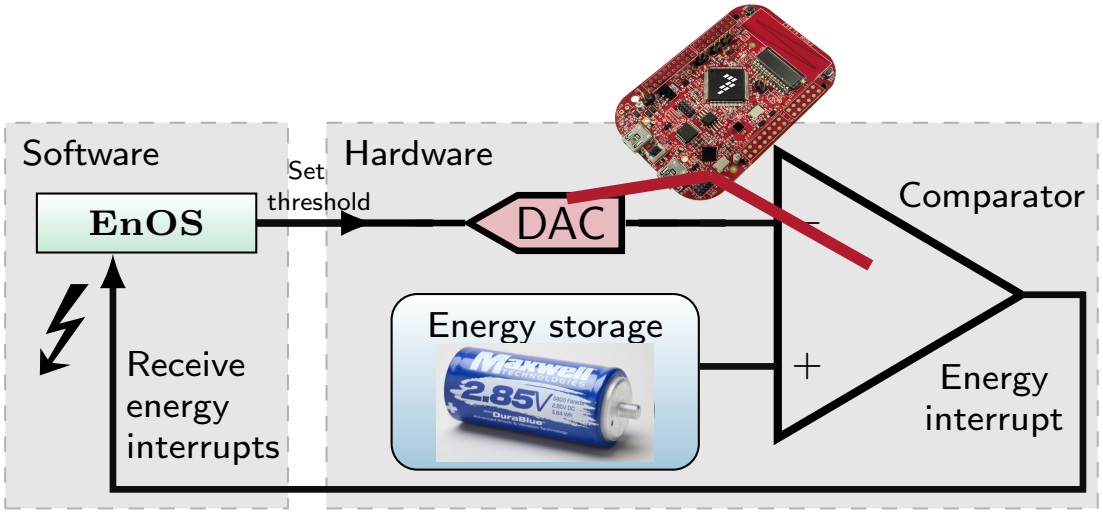


Lightweight Signalling Mechanism for Energy-Related Events

- Monitor budget violations
- **Polling** energy storage
  - **Overhead**
  - Not feasible as **wakeup mechanism** (from deep-sleep modes)

☞ Notifications for energy-related events: ***"energy interrupts"***

Energy-Budget Monitoring – Practical Realization



Exploitation of Commercial Off-the-Shelf Hardware

- Setup notifications
  - Digitial-analog converter: set threshold
  - Comparator: **issue energy interrupt**
- Supercaps
  - Linear relationship between voltage and energy
  - No additional charging circuit for charging
- Used for both **violations and wakeup** for resumption

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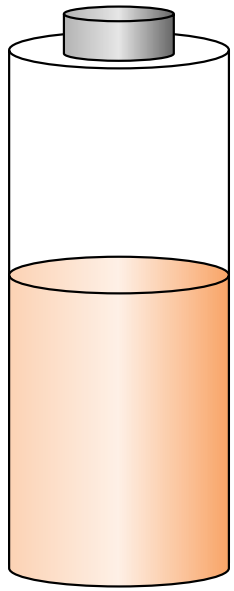
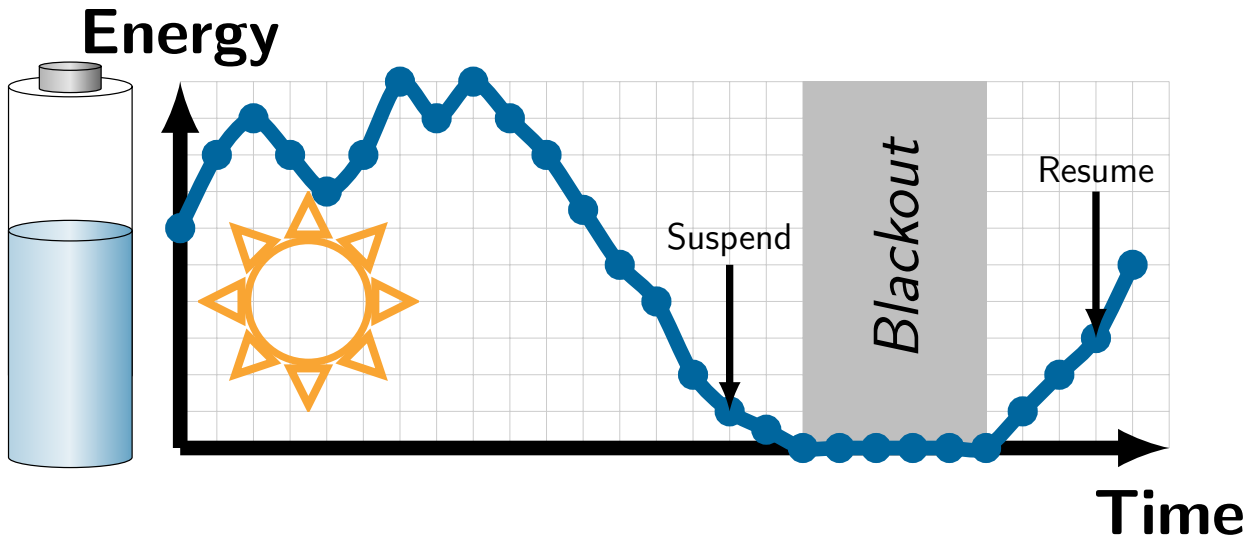


Surviving Blackouts: Problem



When is enough energy harvested?

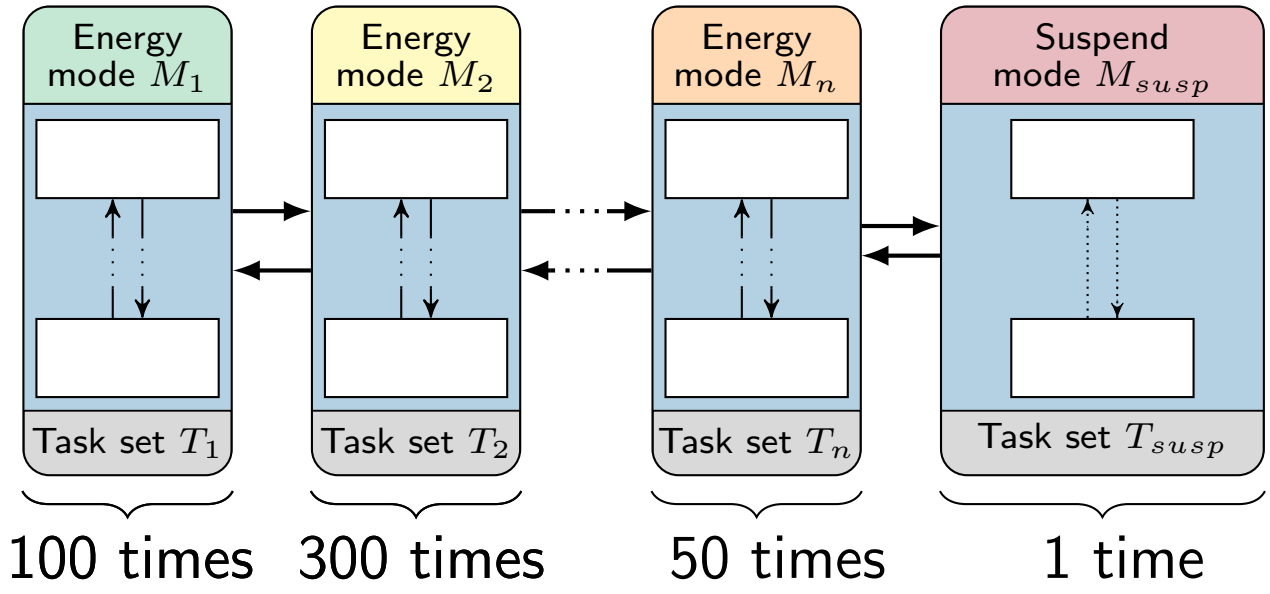
✓ **Suspend early enough**

☞ Exploit a priori **knowledge of WCEC**

- Avoid waking up and immediately suspending
- Forward-looking scheduling required

✗ When to **wake up safely for useful operation?**

Suspension & Resumption



Safe Resumption

- Minimum of hyperperiods executions
- Configurable energy mode for resumption $(M_1, M_2, \ldots, M_n)$
- Allow developer to state *useful work*

  ☞ Wakeup only when **enough energy** to do **useful work**

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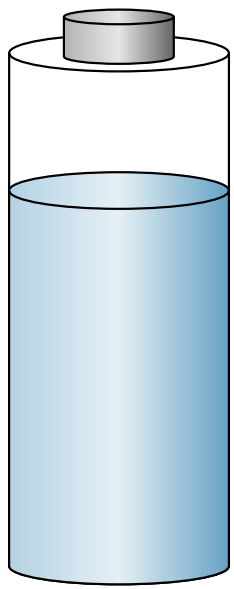
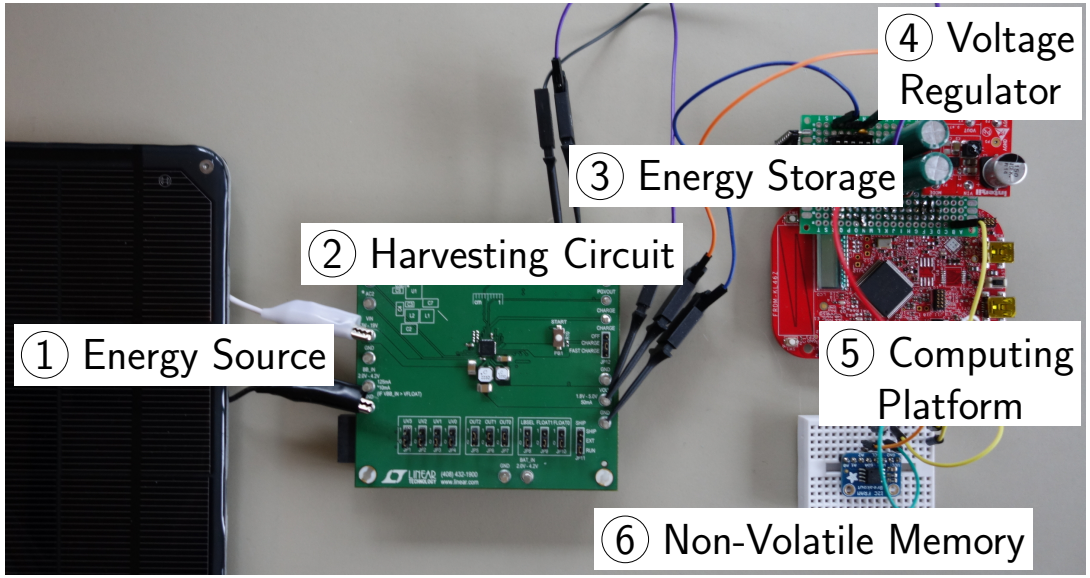


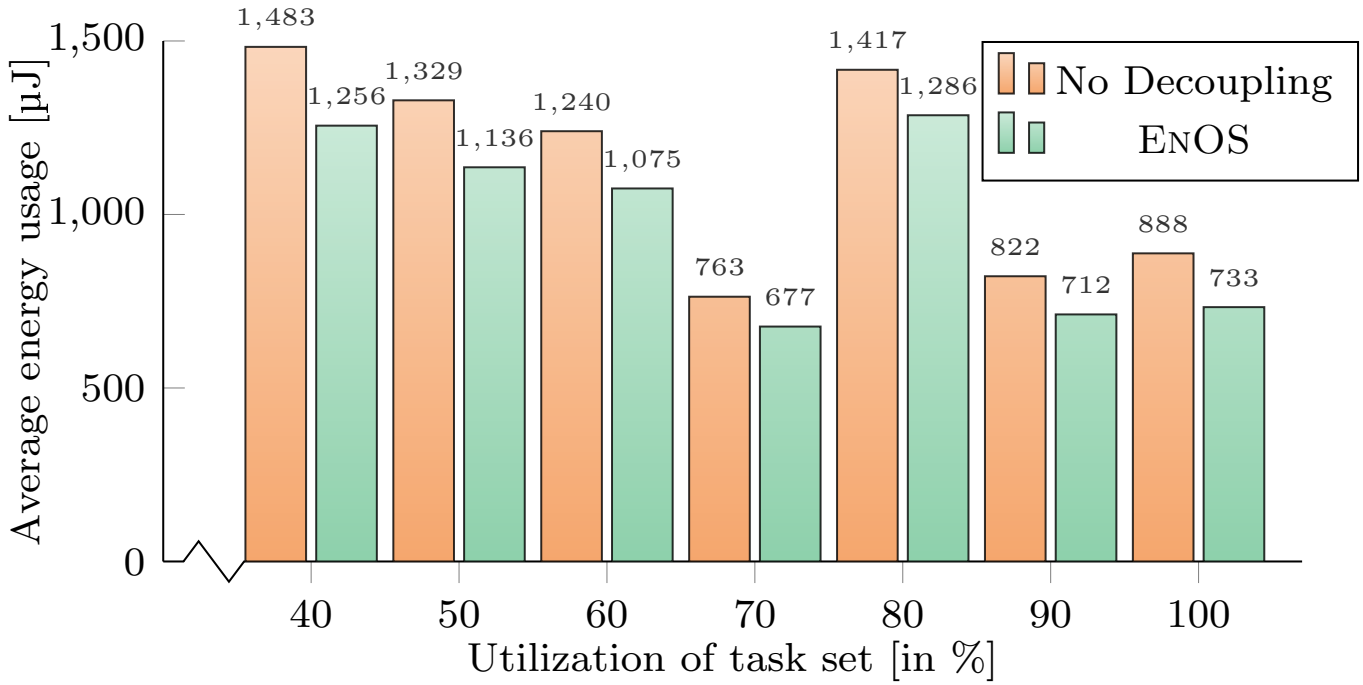
Prototype Hardware Platform



Hardware Components

1. Solar cells
2. Buck-Boost-Converter
3. Supercapacitors
4. Switching regulator
5. Freescale KL46Z: Cortex-M0+
6. Non-volatile FRAM

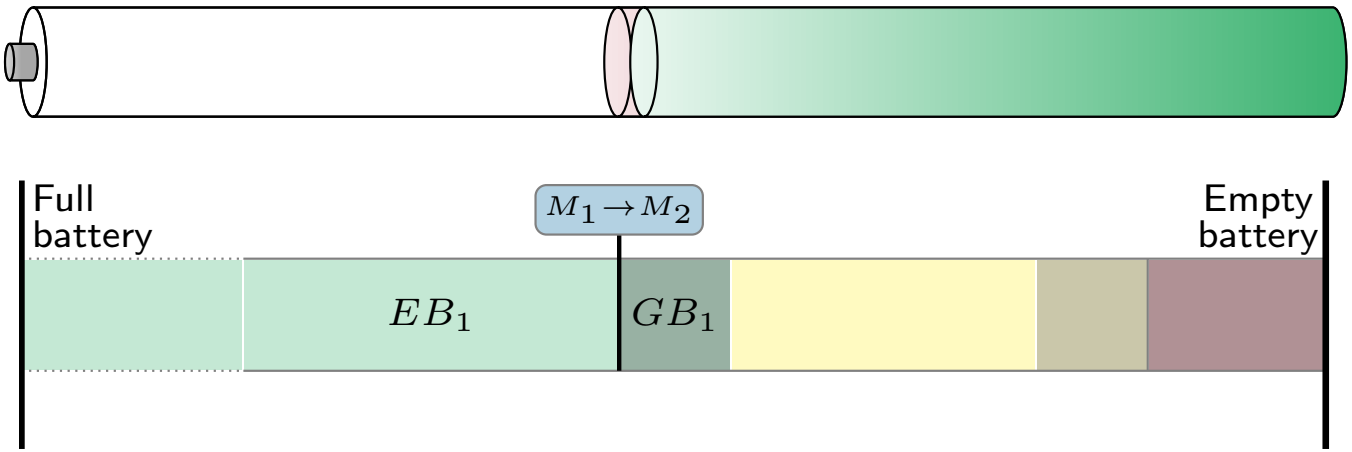
Mode-Dependent Energy Budgets



- Baseline: coupling of WCET and WCEC (using EA-OCBP)
- Synthetically generated task sets (using UUniFast)
- Criticality factor between $E(HI)$ and $E(LO)$: 0.7 x

☞ Up to **17.5 % smaller energy budget**

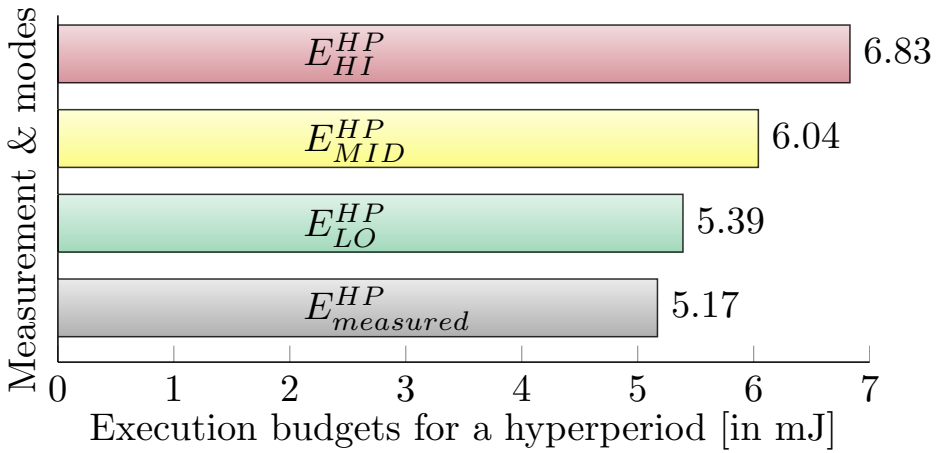
Evaluating Energy Interrupts



- Setup *energy interrupt* and monitor offset
- **Worst-case resolution: 198 mJ** (mean: 94 mJ, few seconds)
- Useless as basis for single scheduling decisions of tasks

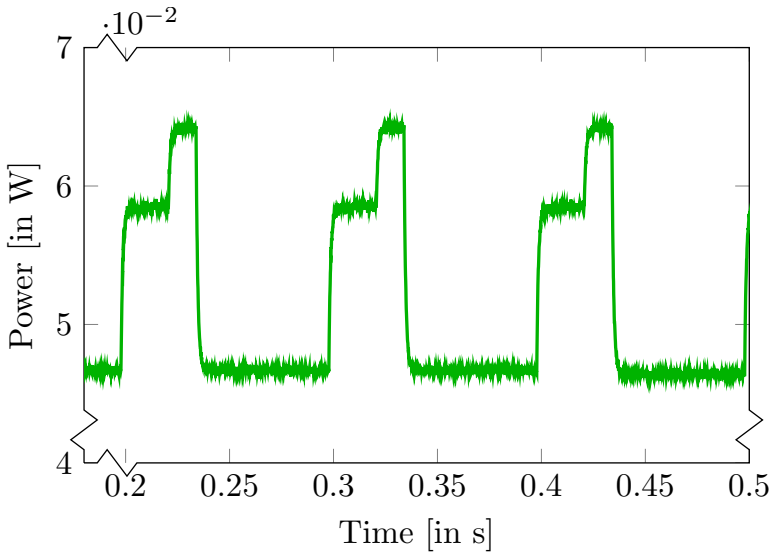
☞ **Feasible to monitor modes**

Precision of Execution Budgets



- WCEC analysis [1] of task set (memory- and CPU-bound tasks)
- Pessimistic, but safe E^{HP}_{HI}
- Precise computation of E^{HP}_{LO} (respecting overheads & idle times)
- **Smaller budgets (21 %, 11 %)**

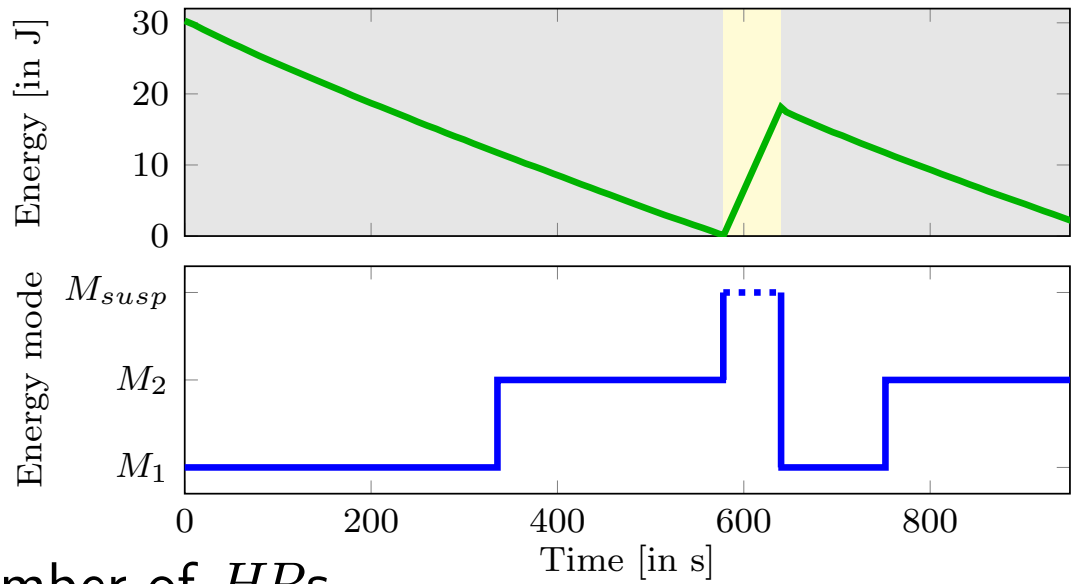
☞ **Enable switch back earlier** when energy is less critical



[1] Wägemann et al. Worst-case energy consumption analysis for energy-constrained embedded systems. ECRTS 2015

Evaluating Energy-Mode Switches

- Energy and mode trace on hardware
- Configured hyperperiods: M_1: 1000 x (100 s), M_2: 2000 x (200 s)



- Requested number of HPs on mode fulfilled ✓
- Low offsets of mode switches **between 0.3 % and 3 %**

☞ **Less than grace budget**

Mode Switch	Time	Static $E_{switch}(i)$	Observed $E_{switch}(i)$
$M_1 \rightarrow M_2$	336 s	12,252 mJ	12,218 mJ
$M_2 \rightarrow M_{susp}$	579 s	87 mJ	65 mJ
$M_{susp} \rightarrow M_1$	636 s	17,640 mJ	18,122 mJ
$M_1 \rightarrow M_2$	742 s	12,252 mJ	12,218 mJ

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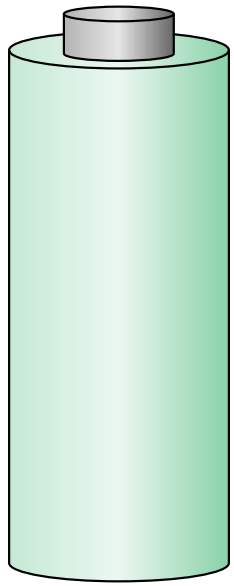
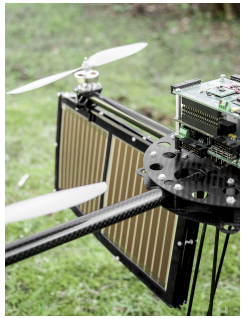


Conclusion

Application Scenario:
Energy-Neutral Real-Time Systems



Scheduling with **Mixed Criticalities** & **Mixed Constraints**

- ✓ Energy-Criticality Modes & Time-Criticality Levels
- ✓ **Multi-mode model: decoupling time and energy**

Energy-Budget **Monitoring**

- ✓ Exploit existing peripherals (i.e., CMP, DAC)
- ✓ Mechanism to wakeup & switch modes: **energy interrupts**

Surviving **Blackouts**

- ✓ **Safe degradation** of services through modes until suspension
- ✓ Resumption when **energy for modes guaranteed**

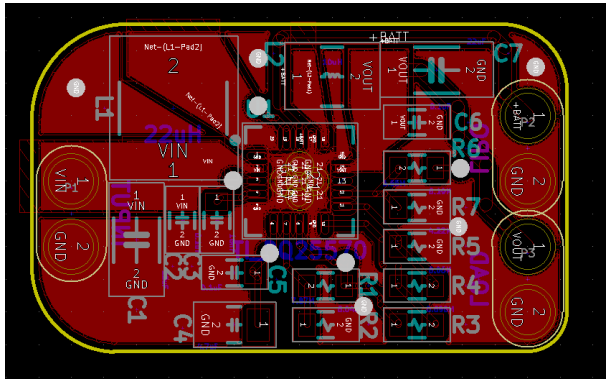
Questions

Get EnOS...

☞ `gitlab.cs.fau.de/enos`

Lots of thanks to...

- **Our anonymous shepherd(s)**
- **Andreas Distler**
- **Peter Ulbrich**



Questions?

Thank you for your attention!