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Real-time aperture synthesis imaging with the DSA-2000 radio camera

2024 Legion Retreat

Martin Pokorny, Caltech

www.deepsynoptic.org

Caltech NANOGrav Physics Frontiers Center Schmidt Sciences

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What is DSA-2000?

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A world-leading radio survey telescope and multi-messenger discovery engine.

- ~2000 x 5m dishes (19 x 15 km)
- Spring Valley, Nevada
- Frequency: 0.7 - 2 GHz band
- Spatial resolution: 3.3 arcseconds
- *Highly optimized for surveys*

Currently in final design phase

Construction start: 2026

First light: 2028

Key surveys: 2028 – 2033

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Unparalleled survey speed

31,000 deg^2 to 500 nJy

>1 billion radio sources (IQUV)

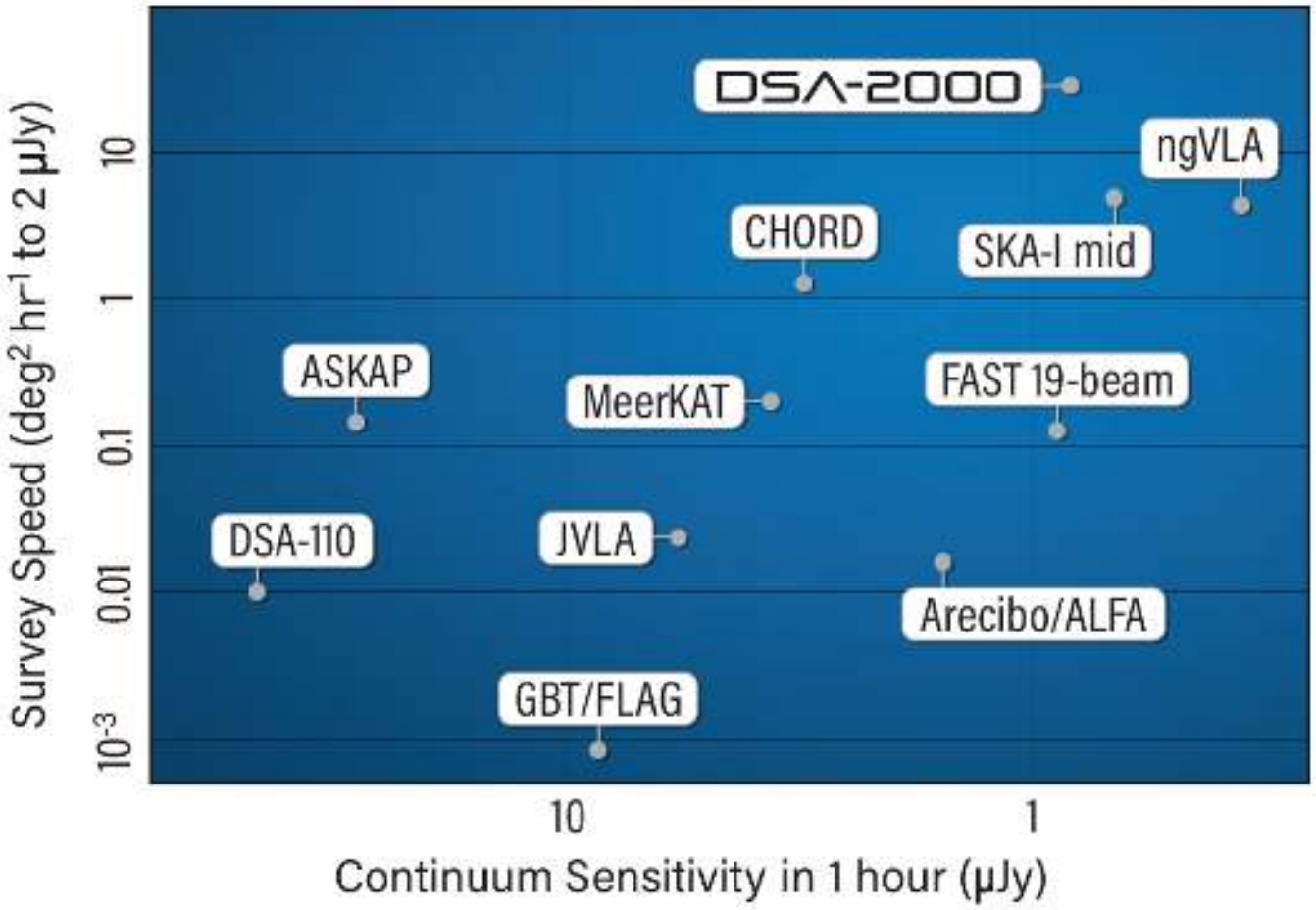
~few million galaxies in HI

~10^5 FRBs and pulsars

~10^6 "slow" transients

Enabled by two key technologies:

- "Radio camera" digital back-end
- Cryo-free antenna/receiver



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What is a radio camera?

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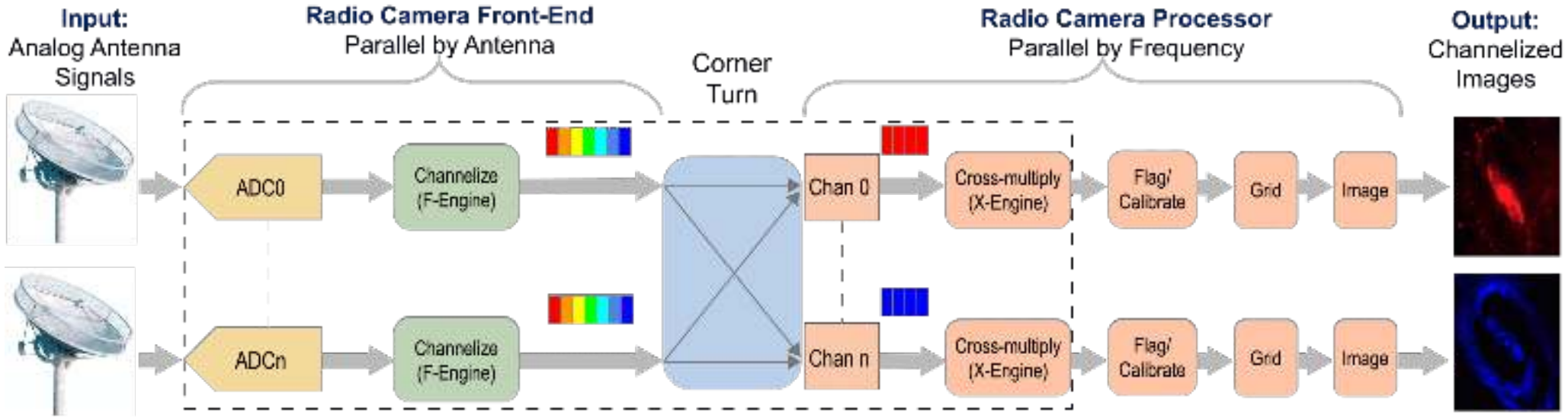
Radio camera schematic



channelized voltage data

voltage data

visibility data

correlator

imaging

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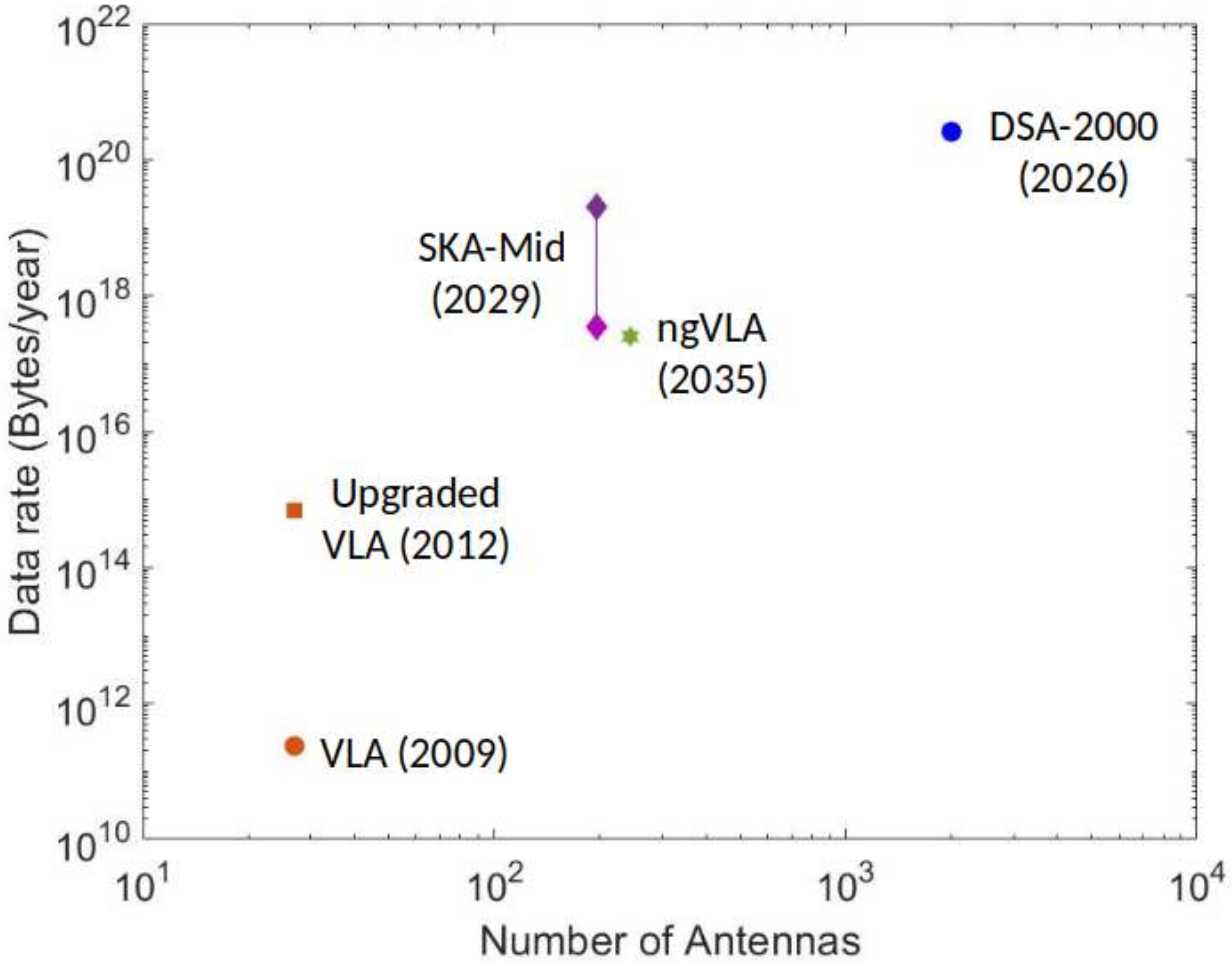
Radio camera motivation

Radio telescope correlator output



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- ~0.8 Zettabytes/yr of voltage data
- 20 Exabytes/yr of visibility data
- $100 million/yr in storage costs to save visibility data

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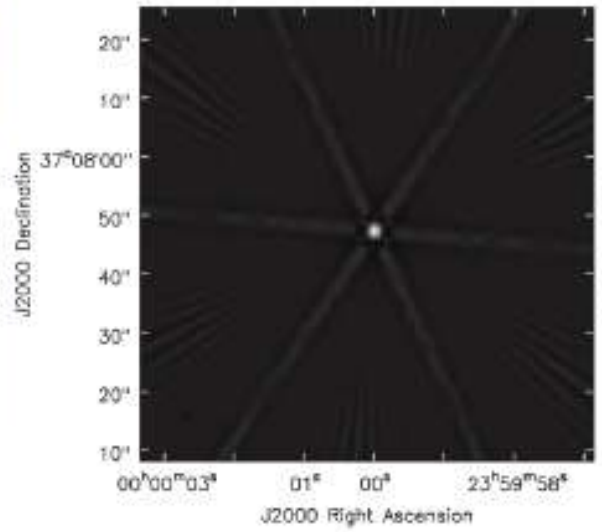
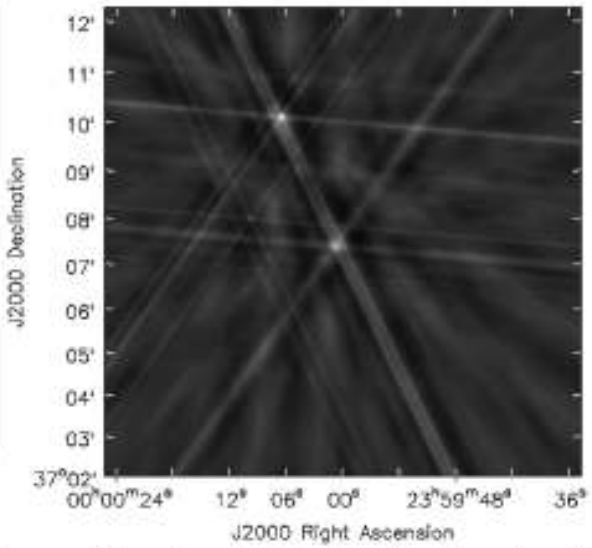
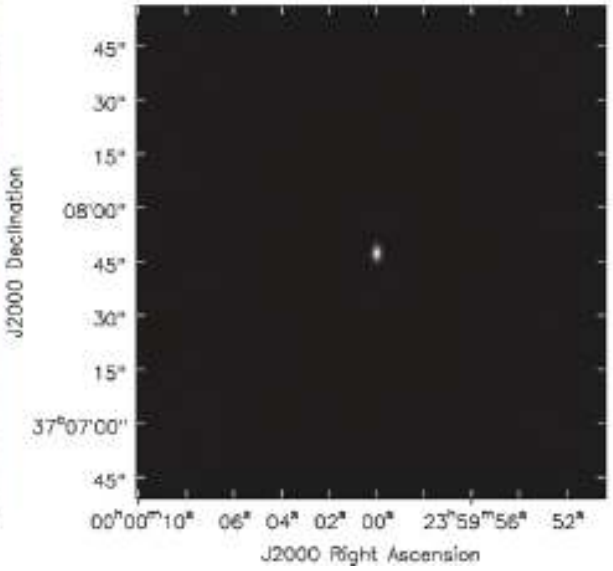
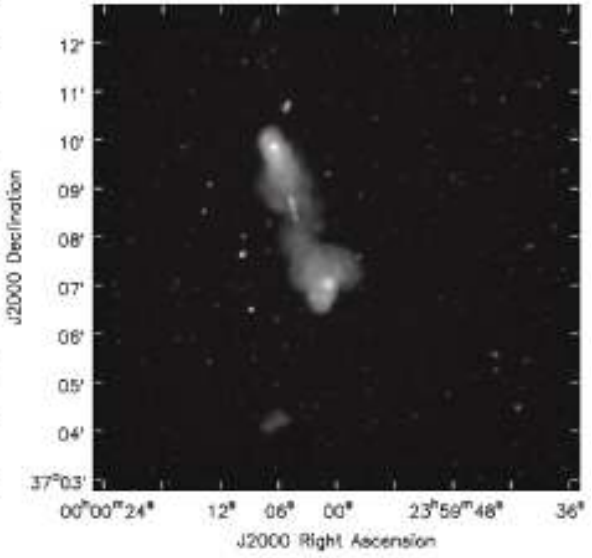
Radio camera imaging









- No need for visibility-based deconvolution
- Enables a deterministic stream processing pipeline that creates images

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Radio camera processing characteristics

- High degree of data parallelism, by frequency channel slices (sub-bands)
  - no cross-sub-band communication, except, maybe...
- Calibration improves with greater bandwidth; may need to span sub-bands.
- RCP input (channelized voltages): 43Tb/s
- RCP output (images): 23 GB/s

Data	**Type**	**Rate (per input channel)**
voltages	4+4 bit complex integer	4 Gb/s
raw visibilities	32+32 bit complex integer	43 MB/s
normalized visibilities	complex single precision fp	43 MB/s
gridded visibilities	complex single precision fp	107 MB/s
grid pixel (updates)	complex double precision fp	~43 GB/s (20x20 CF kernel)

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Radio camera processor deployment

- Goal: 4 input channels per GPU
- All 20 channels in each sub-band are processed by a single node
- 10 GPUs per node: 2 sub-bands per node
  - 3800 GPUs
- baseline GPU: NVIDIA RTX 4000 Ada generation
- 200 GbE network interface (for data input)
- Image output to node-local file system for post-processing

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Imaging pipeline software

symcam

(SYnthesis iMaging CAMera)

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Imaging pipeline inputs

- Data (channelized voltages)
  - for every channel, data arrive from all antennas
  - one input data "stream" for every N (4) contiguous channels
  - each antenna multicasts voltage data *via* UDP on all streams
    - raw data: 7.5 μsec sample time
    - packetized data: several sample times (maximum possible for MTU)
  - metadata: timestamp, stream identification (channels), flag values (bad data)
- Events
  - control messages (*e.g*, start/stop imaging, run bandpass calibration, start/stop diagnostic output)
  - system status metadata (*e.g*, antenna beam patterns, calibration terms)
  - metadata: activation/validity timestamp

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From inputs to regions

- Both data and events are received and buffered by dedicated threads
- Legion tasks launched from the main loop fill regions associated with timestamps with data or events from service thread buffers
- Real-time conditions
  - data timeout: derived from timestamps of received packets
  - event deadline: derived from completion of tasks that fill data buffers
  - no explicit system clock dependency except when no data are received

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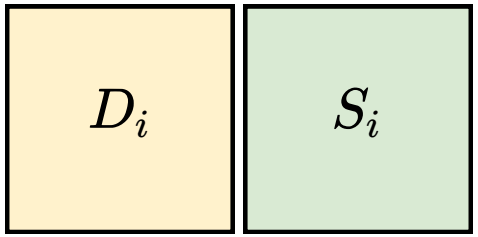
Main loop: input management



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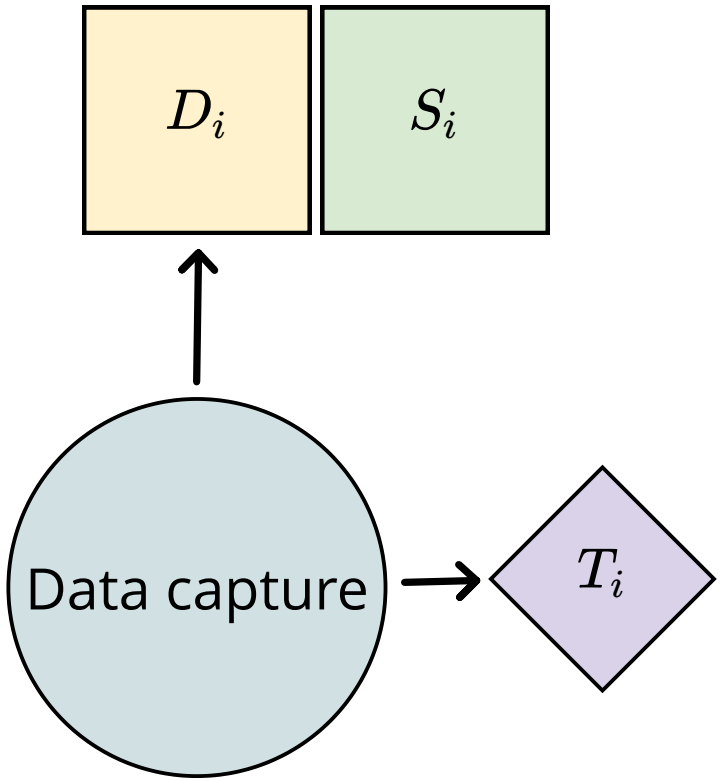

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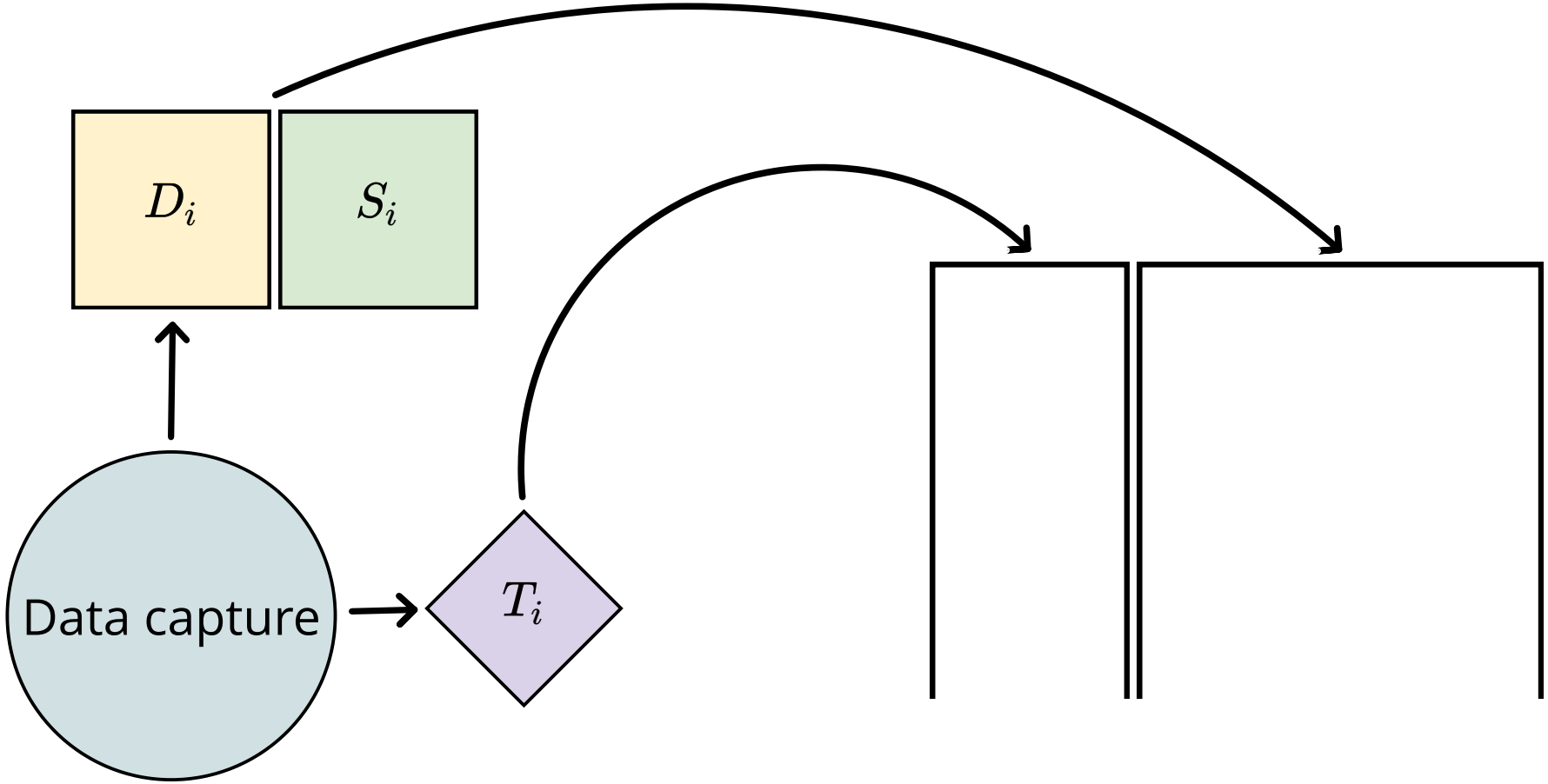

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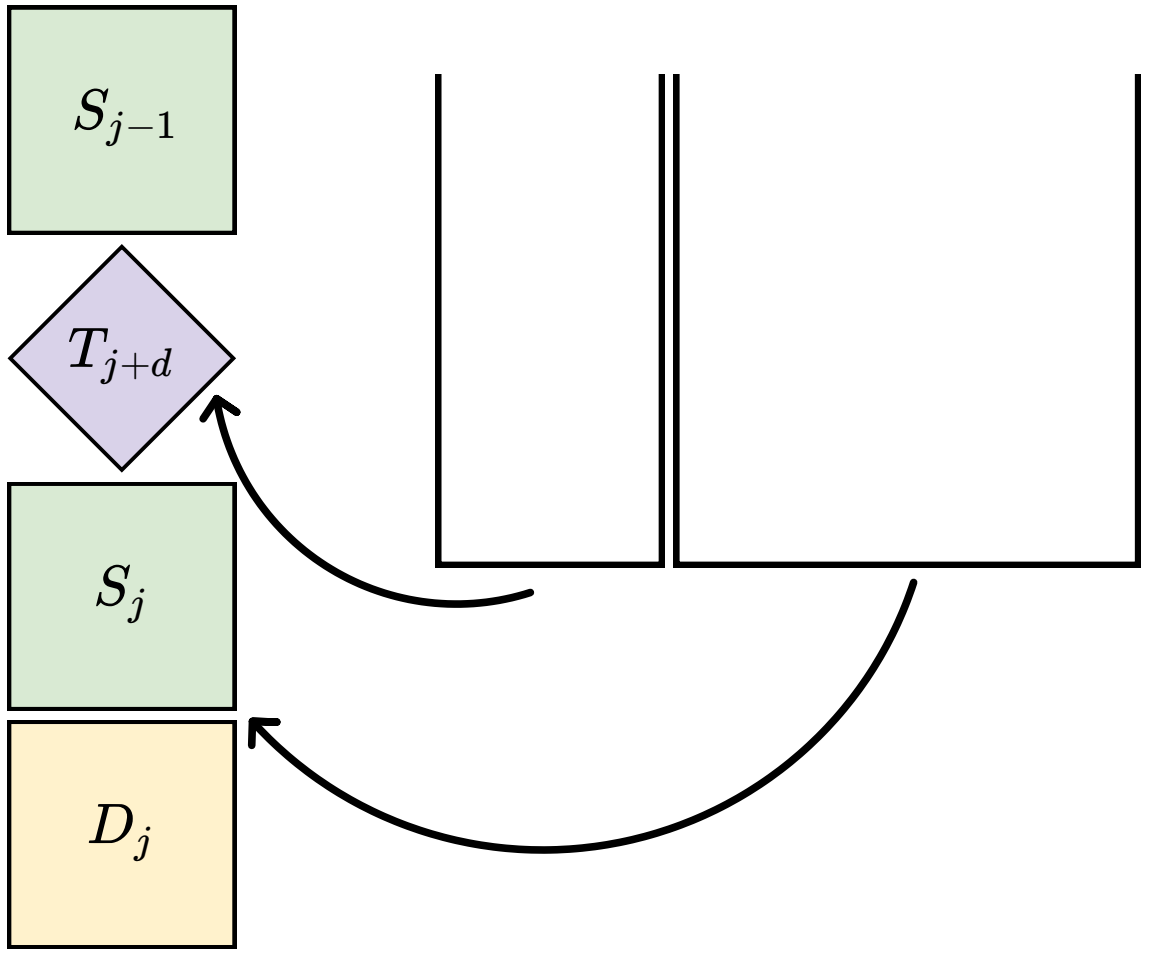

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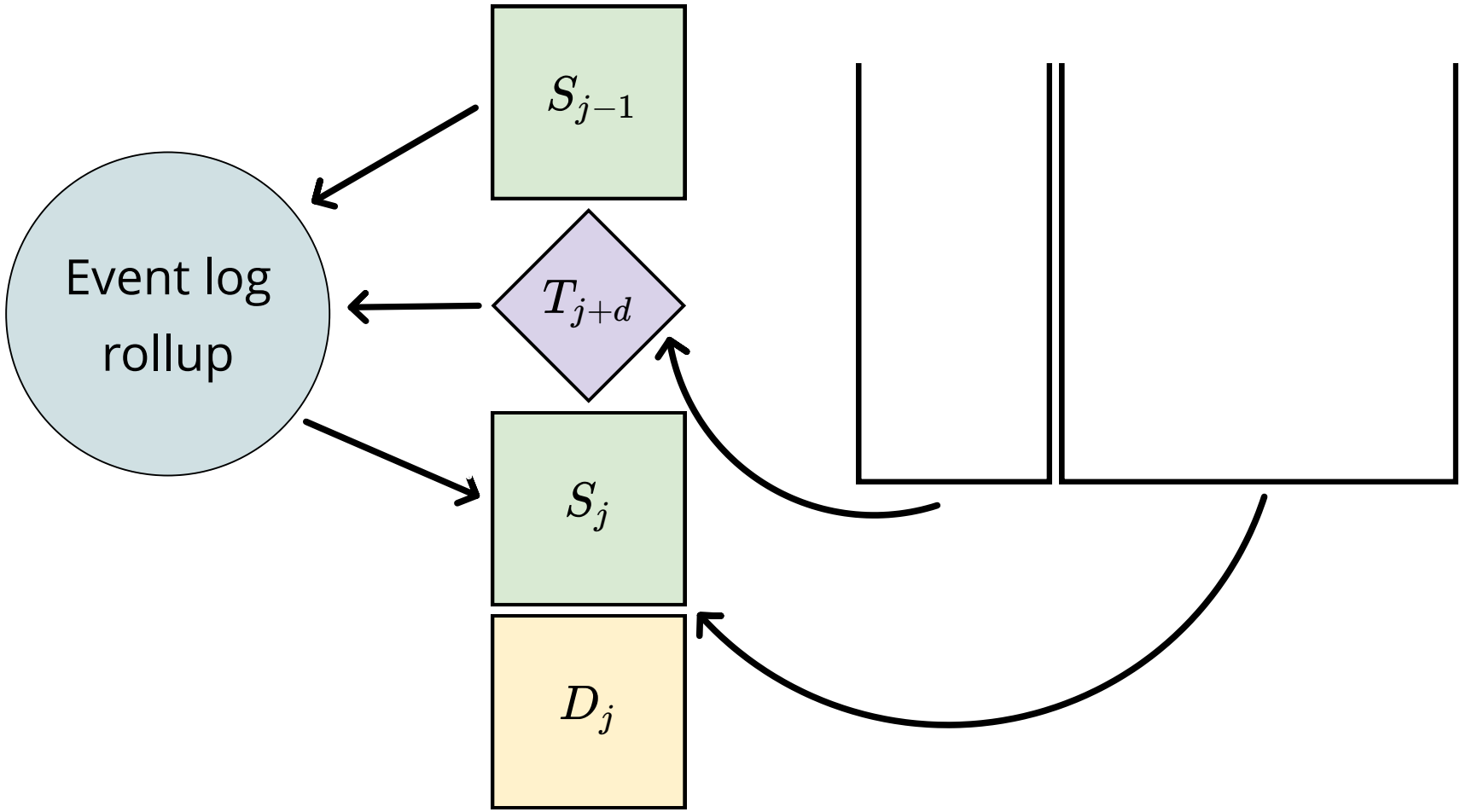

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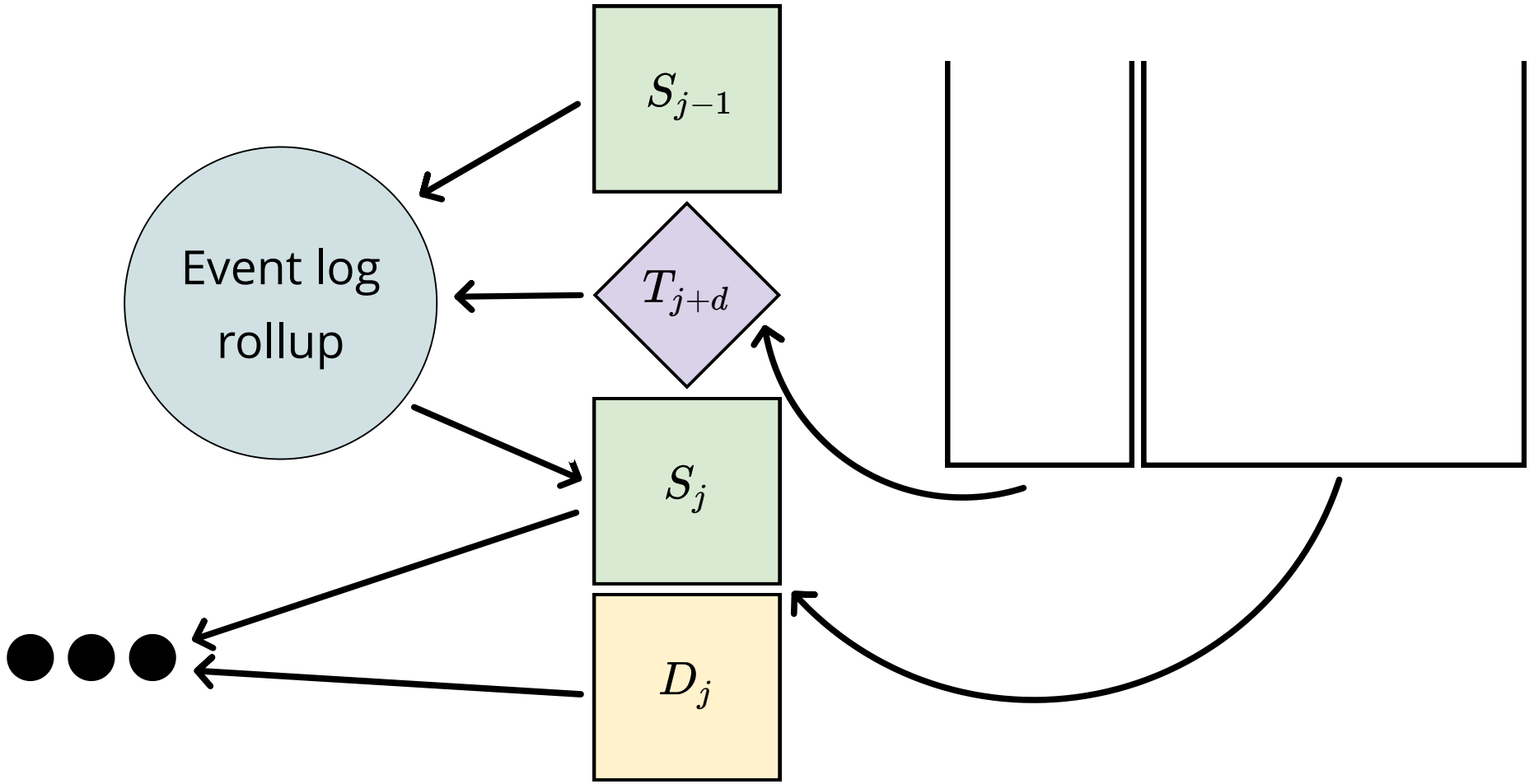

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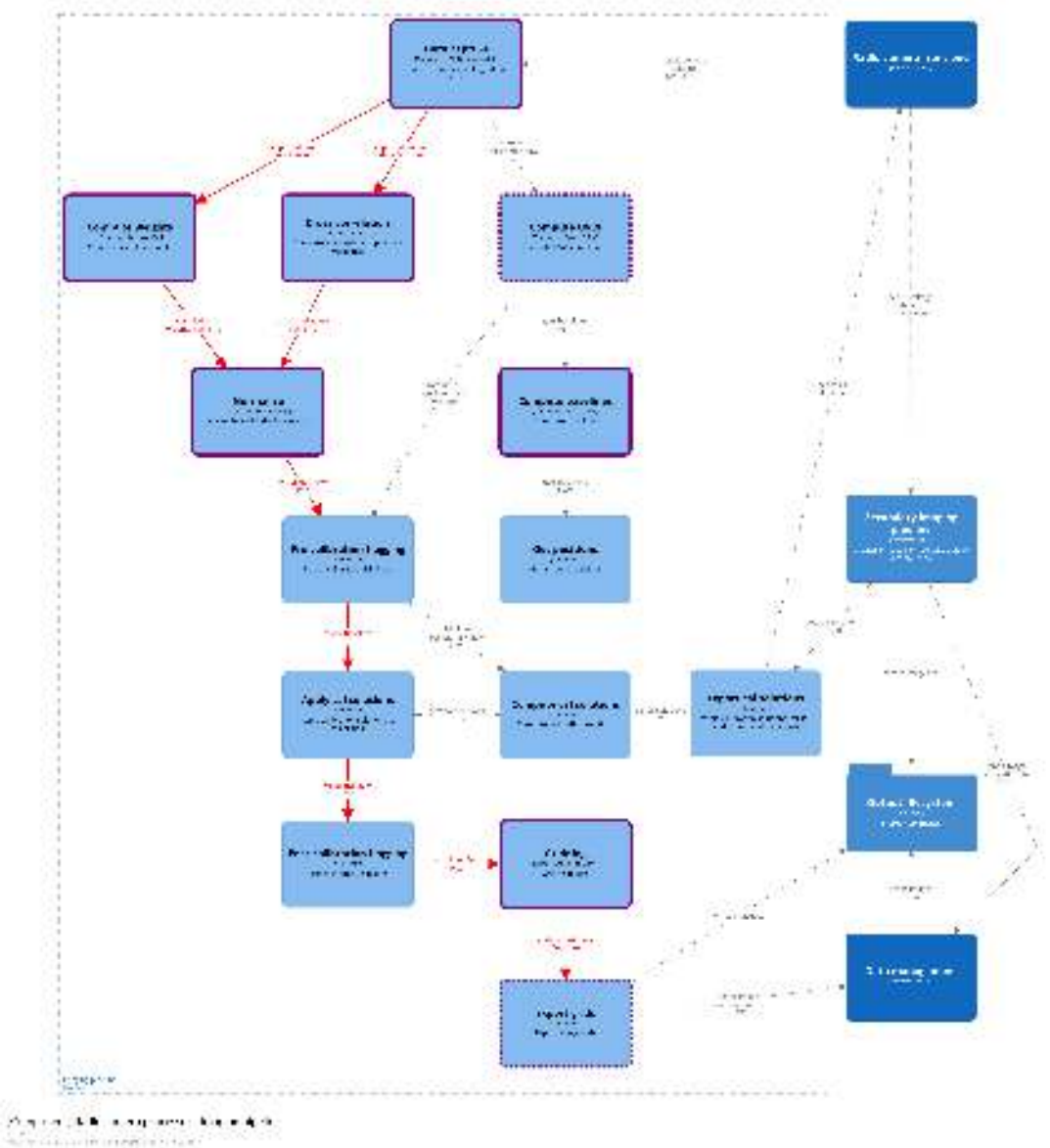
Pipeline states and predication

- a pipeline state is associated with every data timestamp
- states are determined by events
- states determine processing for data with associated timestamps
- pipeline processing is a series of stages, implemented as tasks
- states provide predicates for tasks, effectively making each stage conditional on the pipeline state



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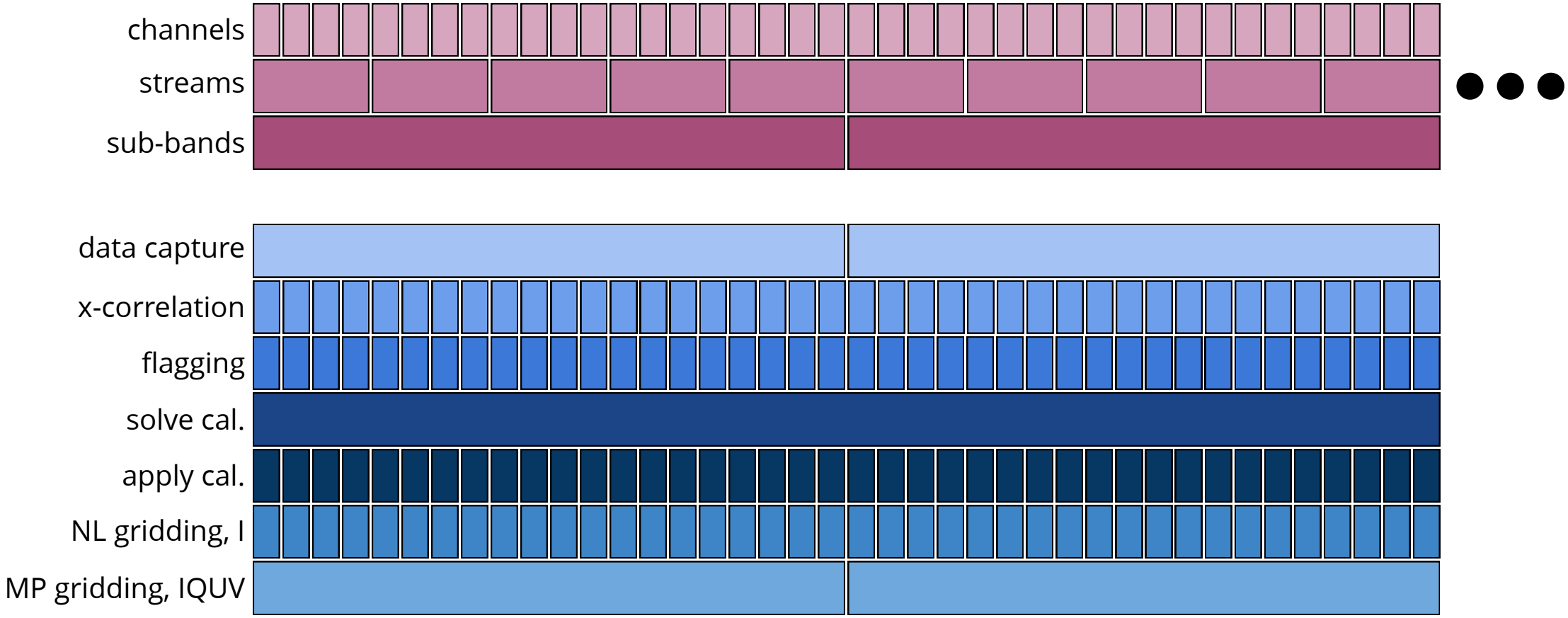
Channel data regions & partitions



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Current status and next steps

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Status

- Events
  - create/destroy subarray
  - shutdown
  - start/stop imaging
  - start/stop flagging
  - start/stop solve calibration
  - start/stop apply calibration (partial)
  - start/stop record data
  - start/stop record events
  - import/export fftw wisdom

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- Stages
  - data capture
  - cross-correlation
  - data weight computation (flag correlation)
  - normalization
  - gridding
  - Fourier transform
  - image export (partial)

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Status

- Events
  - create/destroy subarray
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  - start/stop flagging
  - start/stop solve calibration
  - start/stop apply calibration (partial)
  - start/stop record data
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  - import/export fftw wisdom
- Stages
  - data capture
  - cross-correlation
  - data weight computation (flag correlation)
  - normalization
  - gridding
  - Fourier transform
  - image export (partial)
- Incomplete
  - data flagging (RFI)
  - solve calibration
    - modal (delay, bandpass, polarization)
    - continuous (gain)
  - apply calibration
  - bright source subtraction
  - export calibration solutions
  - import calibration solutions

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Integration with calibration

Current situation

- calibration algorithms developed by domain expert
- implemented using Python
  - numpy
  - JAX
  - Ray
- use inter-process comm with a Ray actor for computing calibration solutions
  - ugly, but may work if averaging is done on Legion side

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Future design

- desirable, but perhaps unnecessary
- Legate
- tasks implemented using XLA

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Main loop refactor

- main challenge of main loop is to run -- not just launch -- data capture tasks ahead of time to avoid losing input data
- restrict main loop to issuing data and event capture tasks, and a single, high-level "input data processing" task, which runs after data and required events have arrived
- all states are known when input data processing task runs -- no predication needed