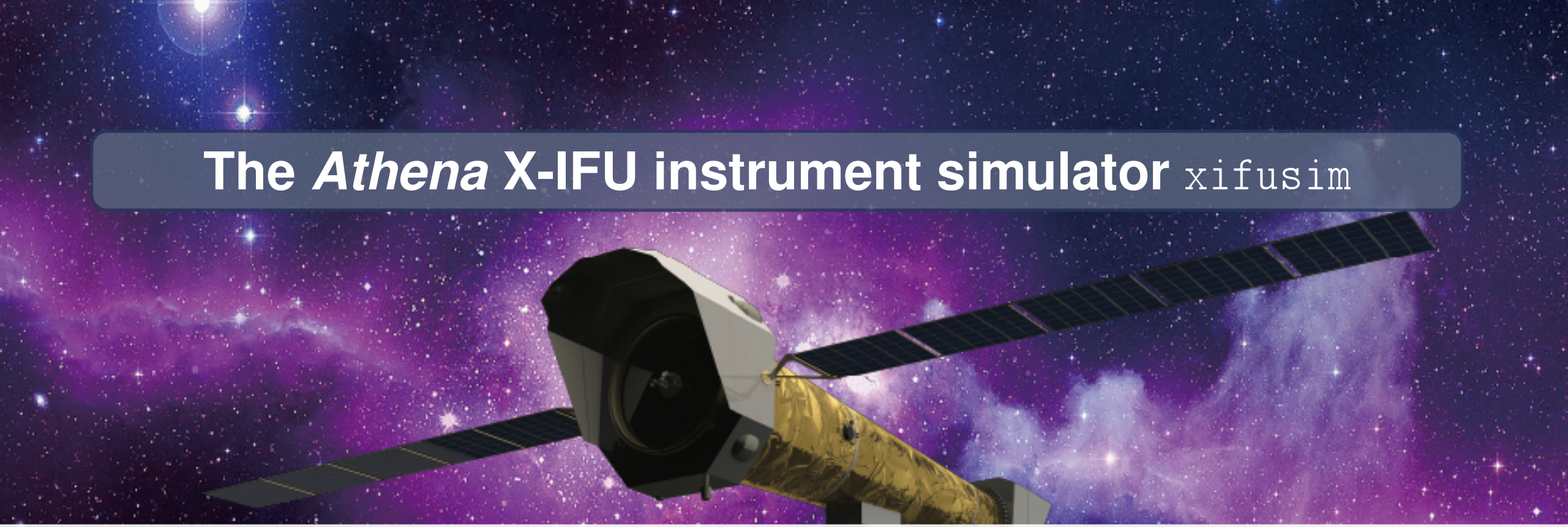
# The *Athena* X-IFU instrument simulator `xifusim`

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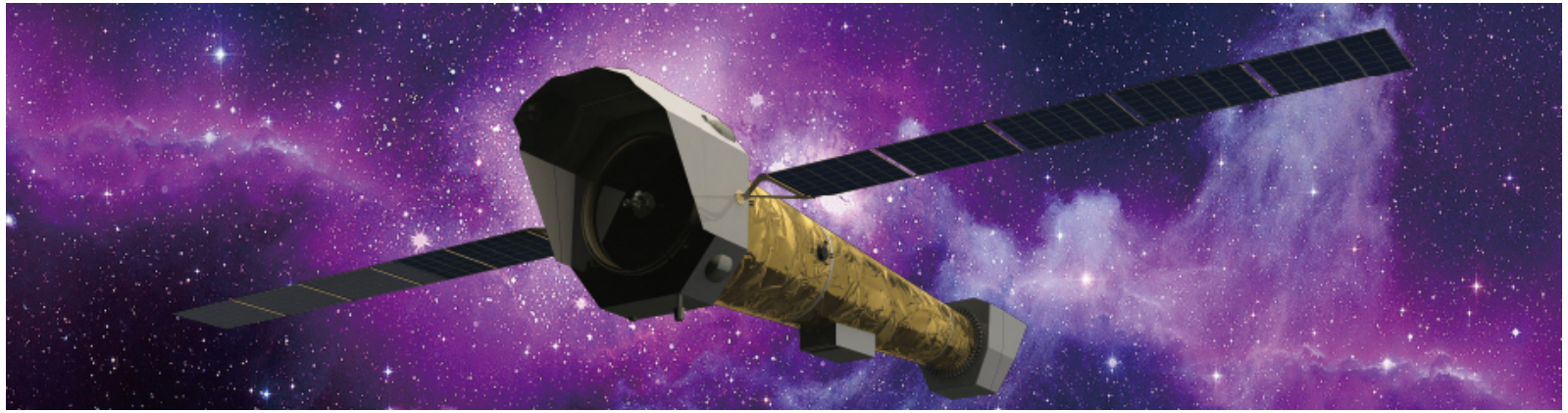
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS


DeMo Workshop, 2021-06-15

ATHENA X-ray Integral Field Unit

# The *Athena* X-ray Observatory



Advanced Telescope for High-ENergy Astrophysics

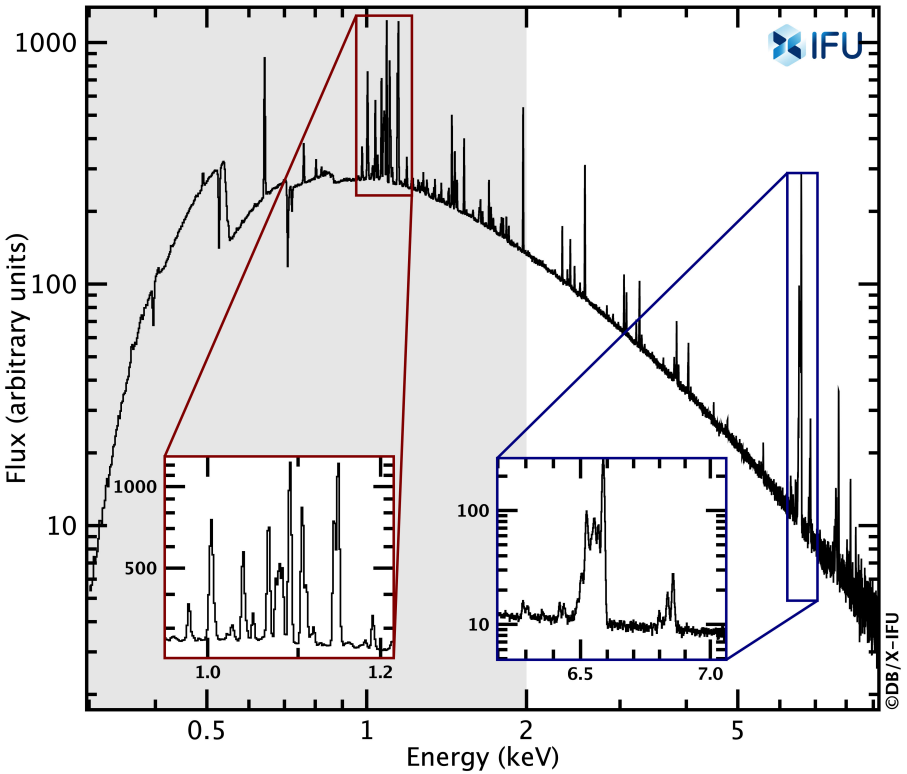
- Second Large-Class mission in ESA's Cosmic Vision Programme
- Launch planned early 2030s with orbit around L1-point
- Science theme: Hot and Energetic Universe, main questions being
  - How does ordinary matter assemble into the large-scale structures we see today?
  - How do black holes grow and shape the universe?

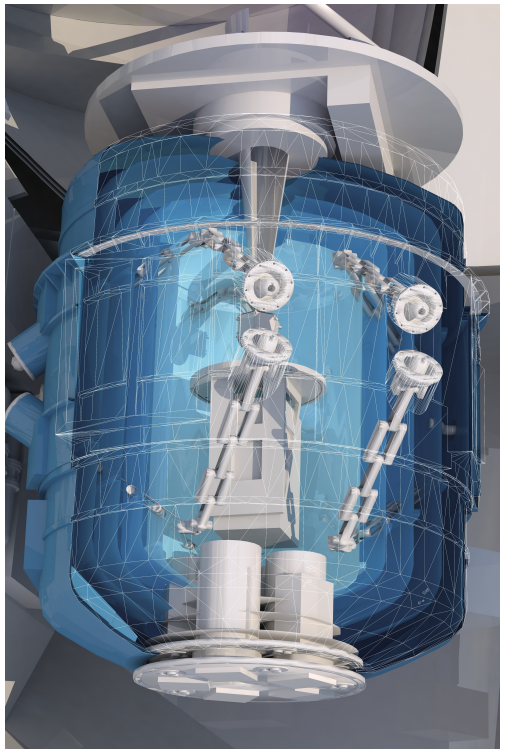
Two focal plane instruments:

- Wide-Field Imager (WFI): DEPFET Detector
- X-ray Integral Field Unit (X-IFU): Microcalorimeter Array

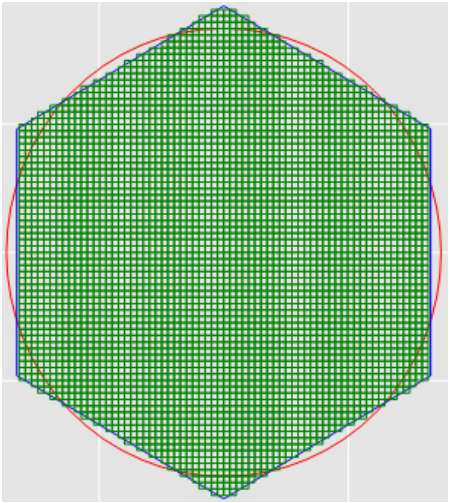
# X-ray Integral Field Unit

- Microcalorimeter for imaging spectroscopy
- Key numbers:
  - Sensitive from 0.2 to 12 keV
  - Energy resolution: 2.5 eV at 7 keV
  - 5′ Equivalent FOV with 5″ pixels (>3000 pixels)
- Utilizes Transition-Edge Sensors (TES)



Left: Artistic view of X-IFU in cryostat [X-IFU Consortium Production, 2019]



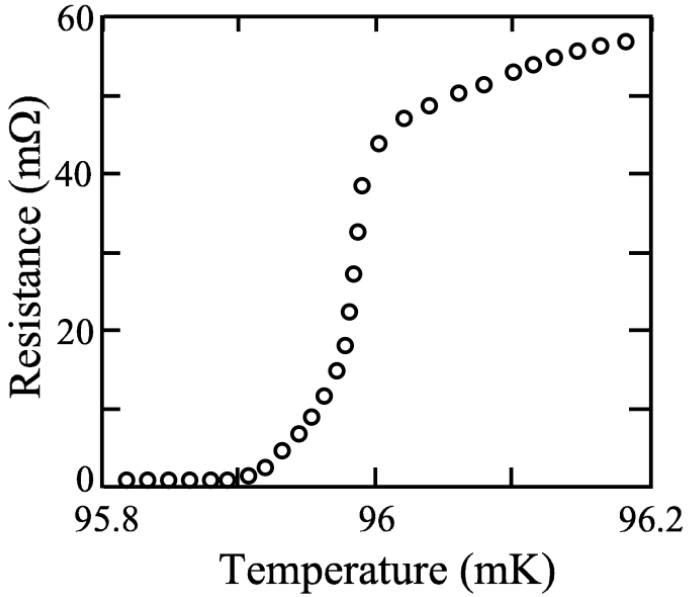
Will provide spatially resolved, high resolution spectra, at energies not reached by grating spectrometers.
Left: Simulated X-IFU spectrum of the Perseus cluster, derived from early Hitomi/SXS observation.

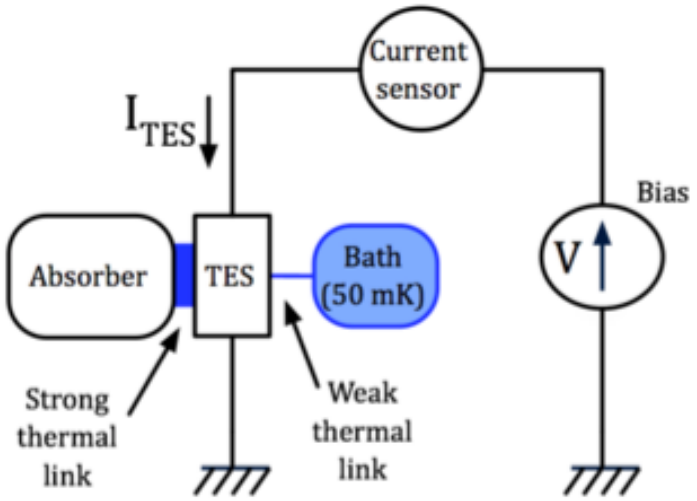
# Transition-Edge Sensors

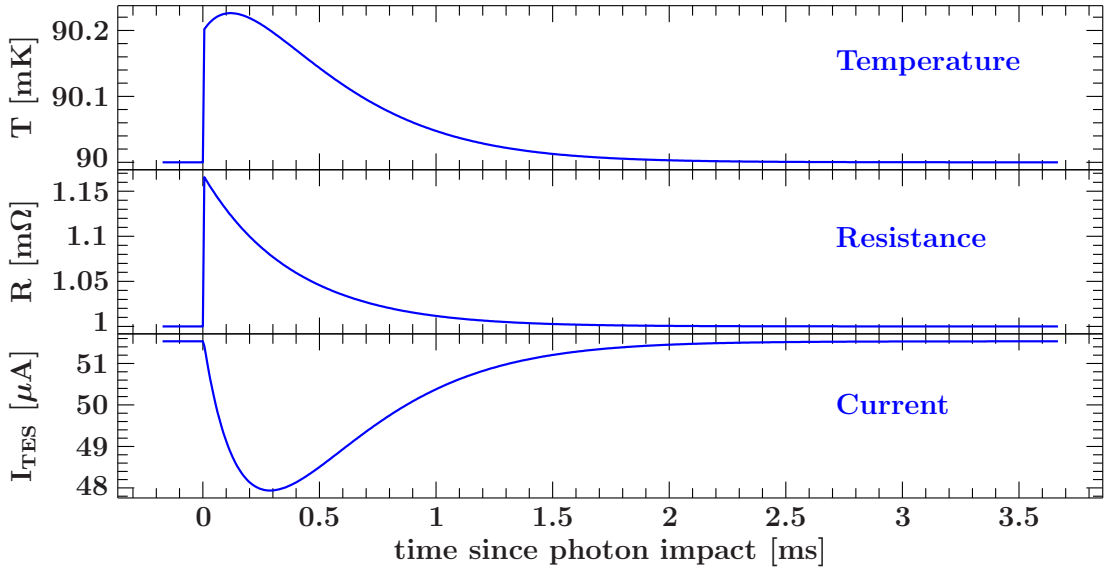
Detection principle for microcalorimeters: Measure photon energy via change in absorber temperature

TES specifically: Thin superconducting strips operated at transition temperature – here $\sim 90\,\mathrm{mK} \Longrightarrow$ Steep $R(T)$-curve

$\Longrightarrow$ When Operating TES in electrical circuit, photon impacts cause energy-dependent current pulses



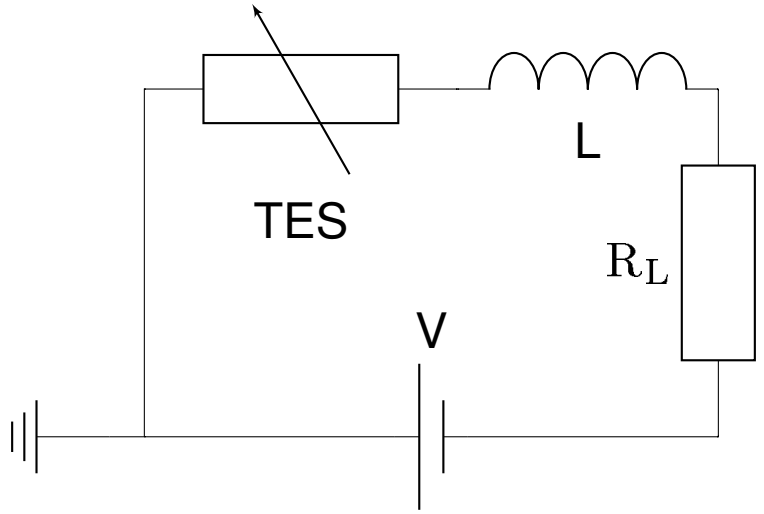
# TES Modelling

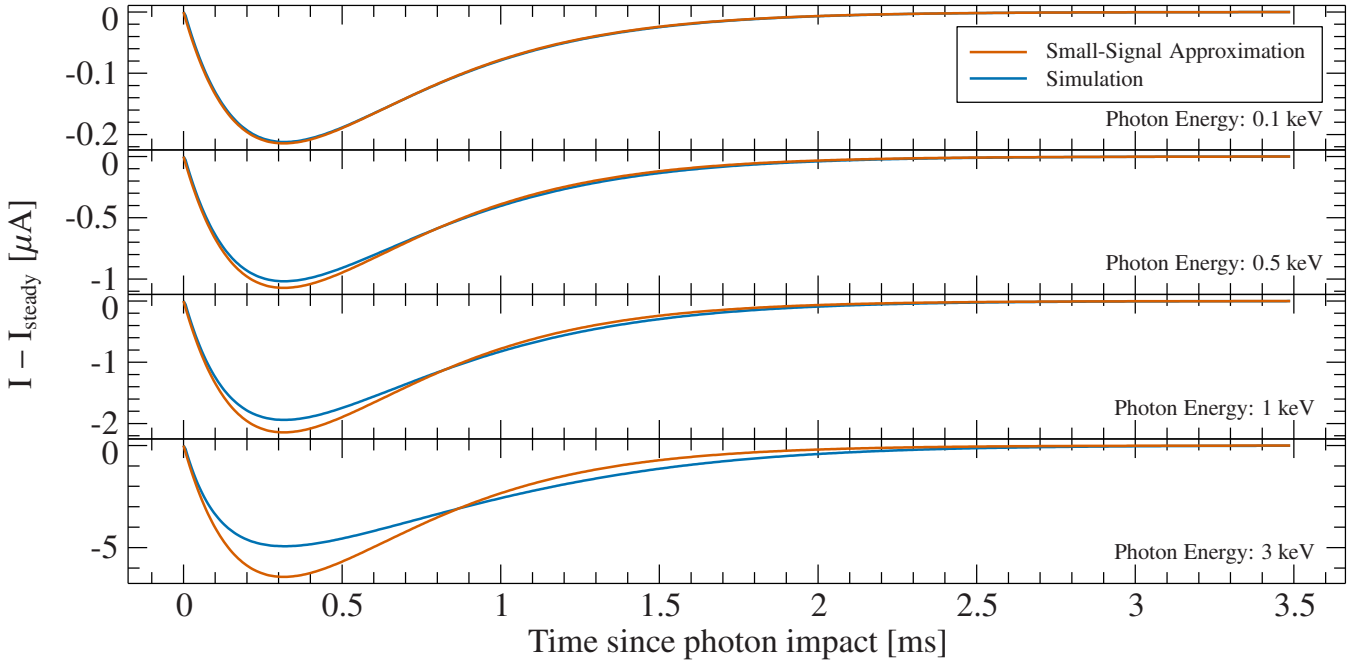
`xifusim` solves the TES differential equations
(Irwin & Hilton [2005])

$$C\frac{dT}{dt} = -P_{\mathrm{b}} + R(T, I)I^2 + P + \mathrm{Noise},$$
$$L\frac{dI}{dt} = V - IR_{\mathrm{L}} - IR(T, I) + \mathrm{Noise}$$

Pulse shape becomes energy-dependent as we leave small signal limit:

$$I(t) \sim \exp(-t/\tau_-) + \exp(-t/\tau_+)$$



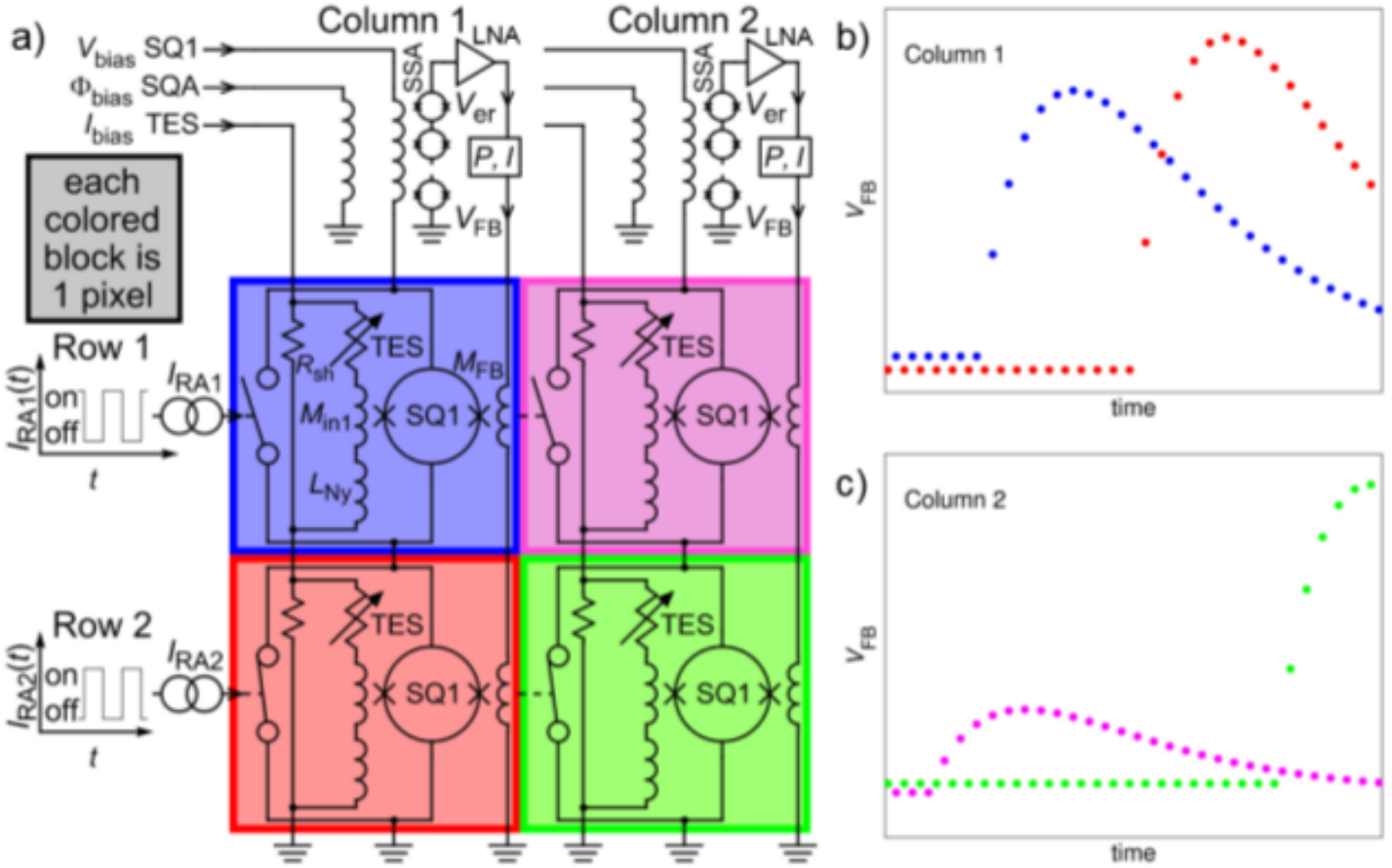



# TES Readout

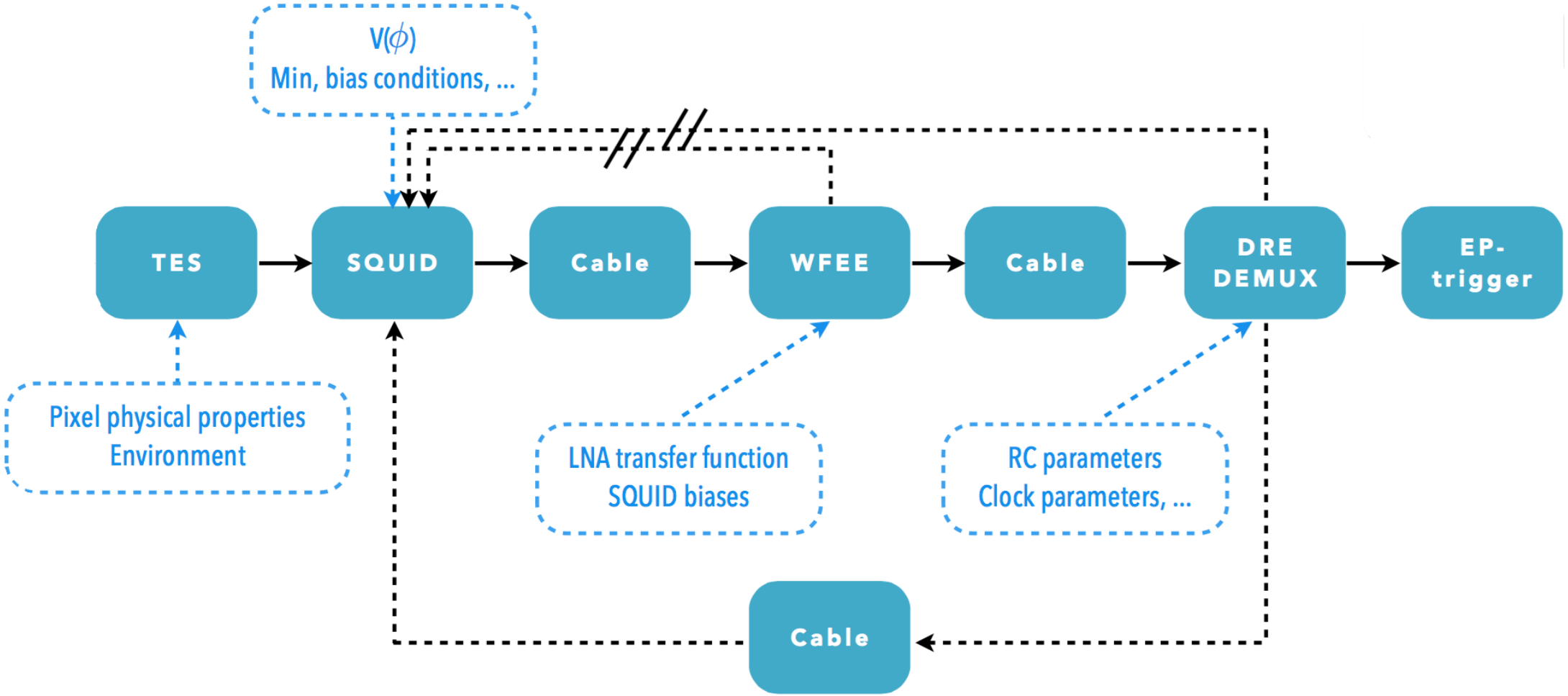
TES readout is typically achieved via SQUID magnetometers followed by further amplifiers and digital readout

Due to large number of pixels (>3000), require use of multiplexing

Current baseline: Time-Division Multiplexing (TDM). Read out pixels in series at sampling rates much faster than pulse timescale.



# Readout chain




Overall readout chain is very complex, with contributions from many different institutes.

Need tools to simulate instrument in detail to study e.g. effects of individual parameters on overall performance!

# Simulators

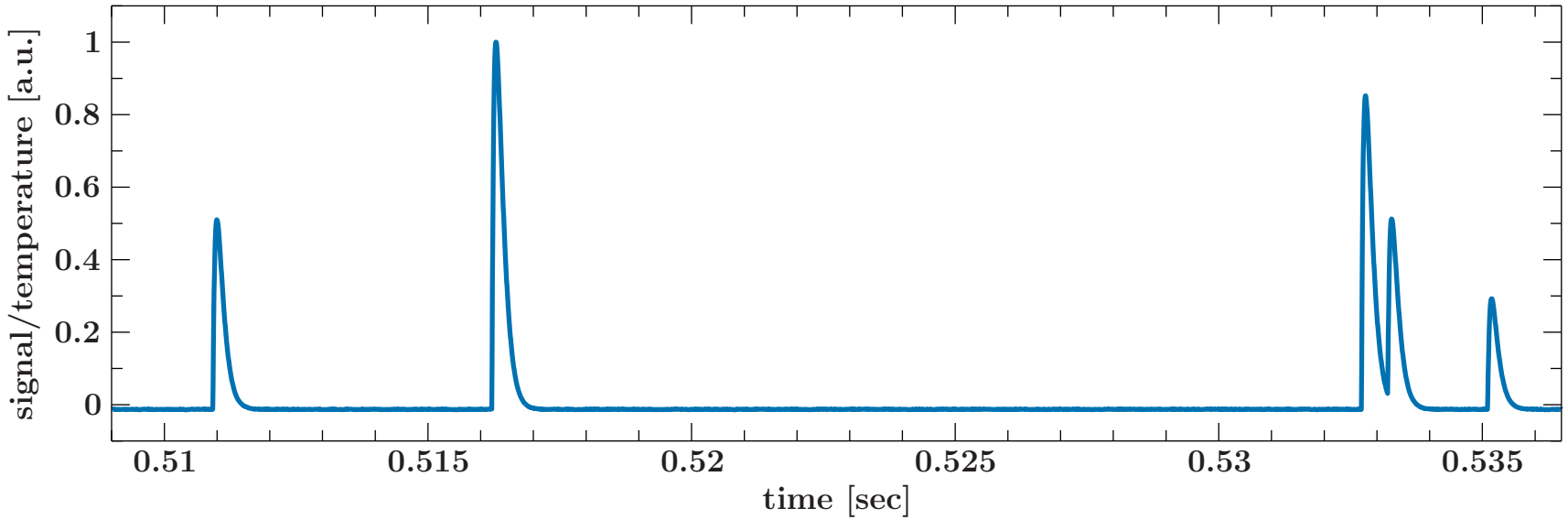
Two simulation approaches:

SIXTE (`xifupipeline`):

- Event-based simulator (simulation time scales with # of photons)
- Simulate detector physics (energy resolution, crosstalk, . . . ) based on precomputed tables
- Rate-dependent energy resolution

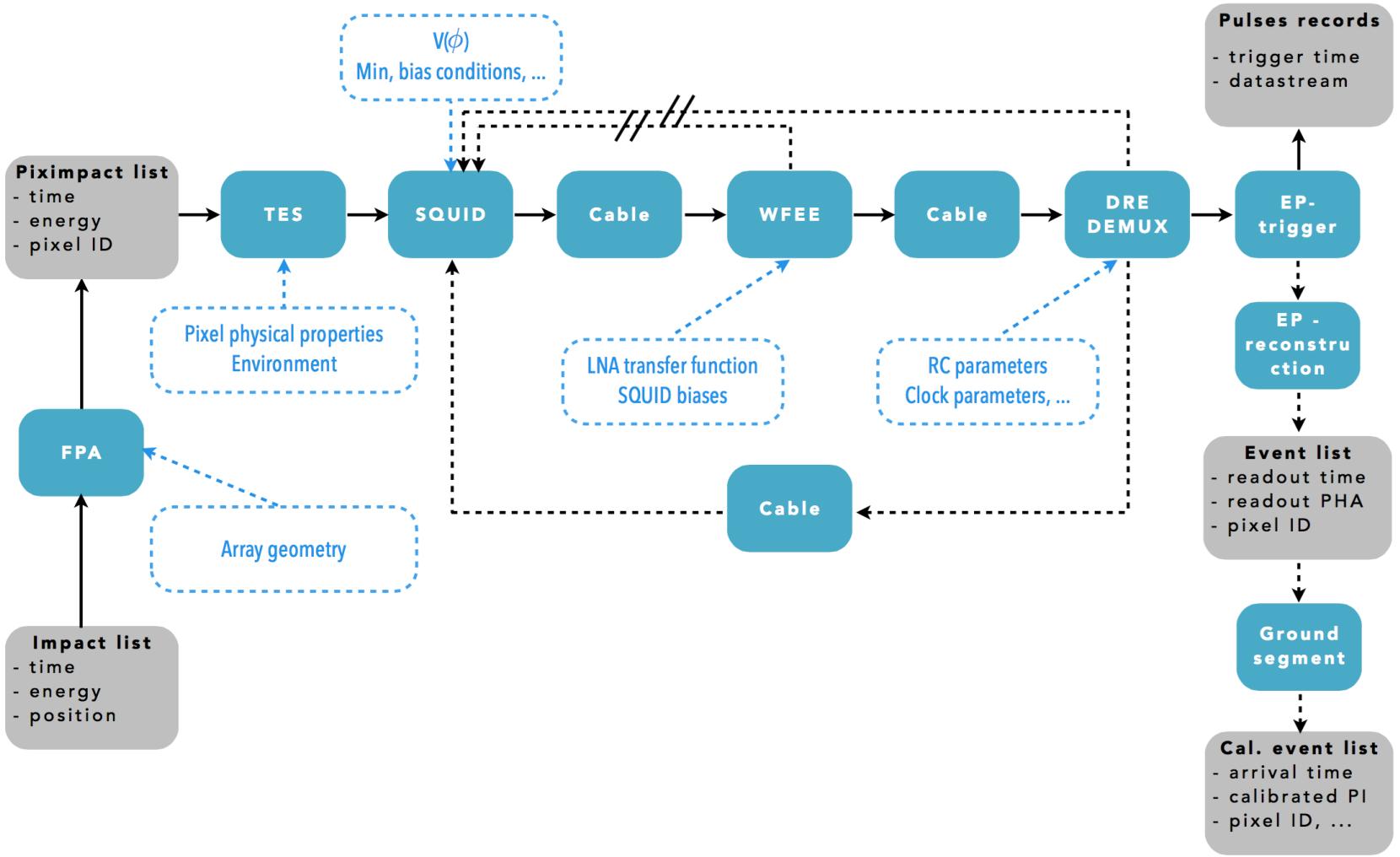
`xifusim`:

- Simulate TES and readout chain in detail
- Produce raw instrument data streams, with energy reconstruction handled by external tools (e.g. SIRENA)
- Provides table data for SIXTE



Dedicated instrument simulator xifusim

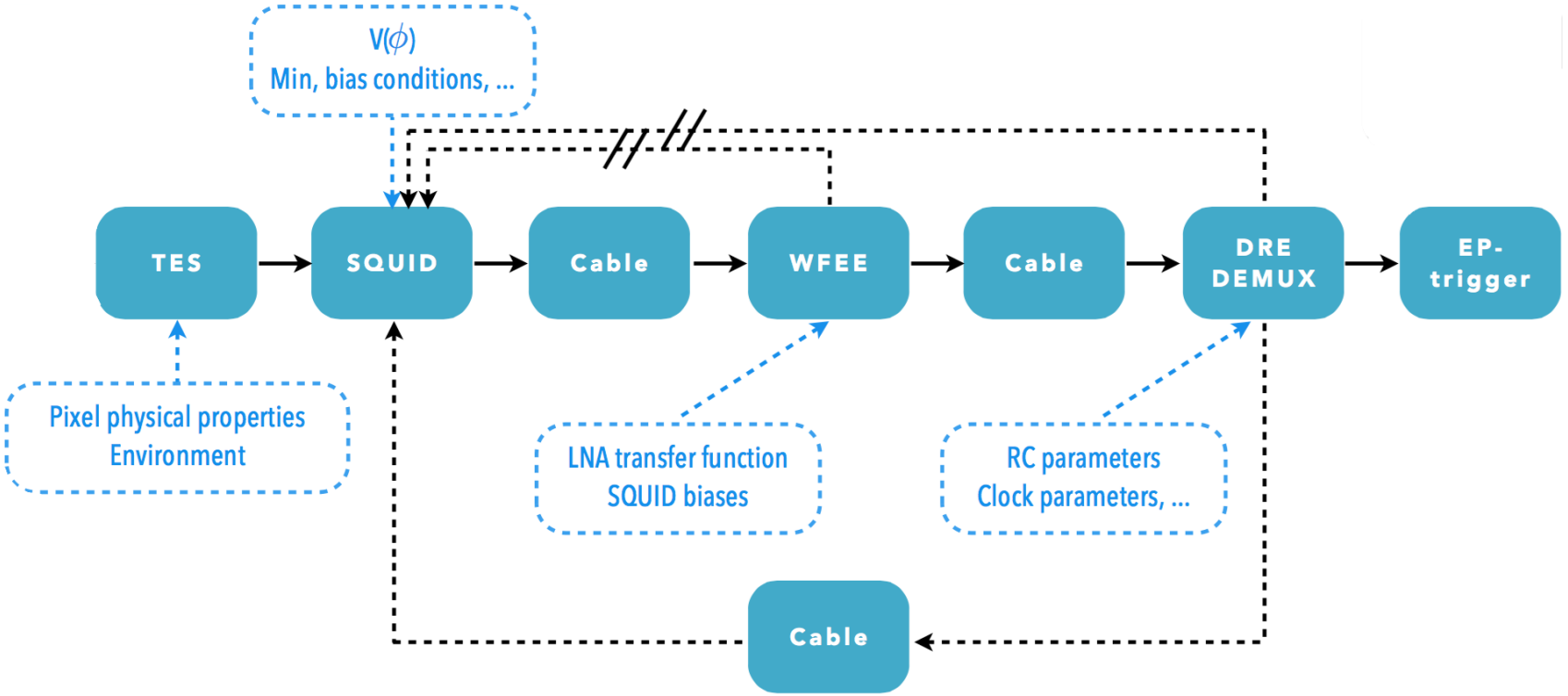
- Based on previous TES simulator tessim, now handling full readout chain
- Written in C++
- Models detection process from impact of photons to triggered record streams




Two main goals: Enable performance studies and provide input for higher level simulators $\Longrightarrow$ SIXTE

# `xifusim` – Software Design

Main design philosophy: Treat readout chain blocks as individual objects, with interchangeable models for each




In code, handle this via object templates. All blocks fundamentally accept input signal and process it, with some blocks interacting via feedback (e.g. DRE to SQUID).

# xifusim – Software Design

Choice of models is handled via instrument configuration XML file

Example: Single channel of 34 TES pixels, read out in TDM

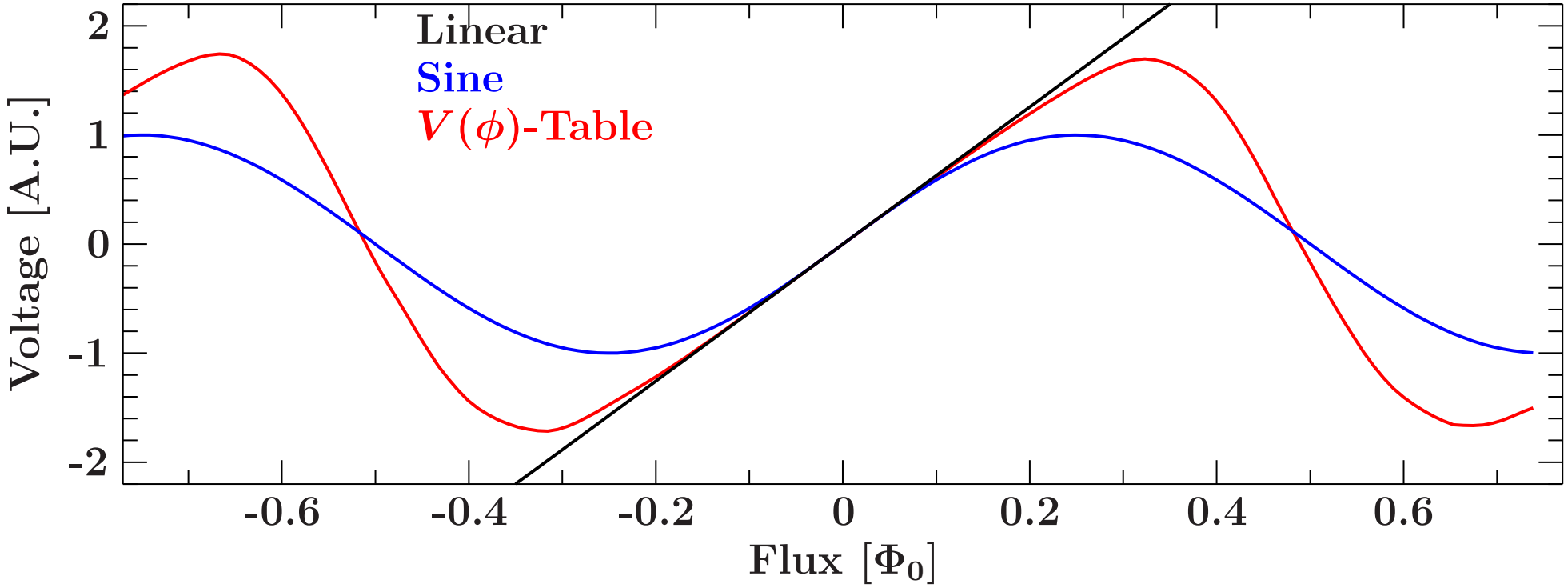
- Individual tags state instrument model, with parameter sets stored in FITS extensions
- Also store data on signal cable bandwidths
- Reconstruction parameters mostly used by later tools.

```
<?xml version="1.0"?>

<xifuconfig>

  <detector model="TDM" filename="pars_tdm.fits" hduname="Lin34_MUX34">

    <TesArray>
      <TES model="LinTES" filename="pars_lpa2.5a.fits" hduname="LPA2.5a"/>
      <ResPixels model="ConstPix" filename="pars_lpa2.5a.fits" hduname="LPA2.5a_Res"/>
    </TesArray>

    <SQUID>
      <MUXSQUID model="SineSquid" filename="pars_lpa2.5a.fits" hduname="Sine_MUX_LPA2.5a"/>
      <AMPSQUID model="LinSquid" filename="pars_lpa2.5a.fits" hduname="Lin_SSA_LPA2.5a"/>
    </SQUID>

    <WFEE model="LinLNA" filename="pars_lpa2.5a.fits" hduname="LinLNA_LPA2.5a"/>

    <ADC model="LinADC" filename="pars_lpa2.5a.fits" hduname="ADC_12_LPA2.5a"/>

    <DRE model="TDM_DRE" filename="pars_lpa2.5a.fits"  hduname="TDM_LPA2.5a"/>

    <Trigger model="TriggerDiff" filename="pars_lpa2.5a.fits" hduname="TrigLPA2.5a"/>

    <Cables>
      <Cable loc="SSA_RA" filt_type="Butterworth" order="1" fcut="10e6"/>
      <Cable loc="SQ1_FB" filt_type="Butterworth" order="1" fcut="10e6"/>
      <Cable loc="SSA_FB" filt_type="Butterworth" order="1" fcut="10e6"/>
    </Cables>


  </detector>

  <reconstruction>
    <ADU_to_I I_BIAS="3.989768e-5" ADU_BIAS="7086.5268" ADU_CNV="-8.345369e-9"/>

    <grading num="1" name="vhigh" pre="494" post="8192"/>
    <grading num="2" name="high" pre="494" post="4096" />
    <grading num="3" name="inter" pre="494" post="2048"/>
    <grading num="4" name="med" pre="494" post="512"/>
    <grading num="5" name="lim" pre="494" post="256"/>
    <grading num="6" name="low" pre="494" post="8"/>
  </reconstruction>

</xifuconfig>
```

# `xifusim` – Software Design

Example: Transfer function of a SQUID amplifier: Provides output voltage as a function of magnetic flux

- `LinearTransfer`: Linear conversion of flux to voltage
- `SineTransfer`: Sine with given amplitude, periodic in magnetic flux quantum $\Phi_0$
- `VphiTransfer`: Interpolate output current from a given $V(\phi)$ table



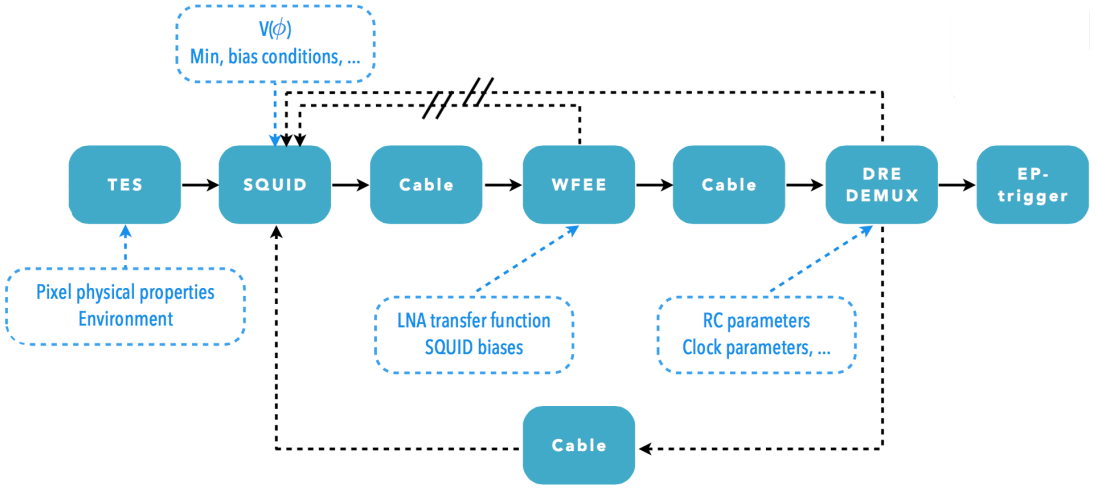
# xifusim – Further Features

Aside from modularity two main features enable detailed studies:

## Output Granularity

Can toggle the writing of intermediate block output, as well as internal block states

```
<?xml version="1.0"?>
<!--This is a comment-->
<commands>

  <!--Add a sine on top of the direct line gain-->
  <CMD type="Sine" block="SQUID" param="direct_line_gain" id="0"
    tstart="0." tstop="100."
    amp="0.2" freq="1000." phas="0."/>

  <!--Sweep pixel 1's bias voltage according to a table-->
  <CMD type="Interpolate" block="TES" param="V0" id="1"
    tstart="0." tstop="100."
    table="IV_vals.fits"/>

  <!--Sweep pixel 2's bias voltage up...-->
  <CMD type="Sweep" block="TES" param="V0" id="2"
    tstart="0." tstop="0.025"
    start="0." stop="10e-9"/>

  <!--...and then hold it there-->
  <CMD type="Sweep" block="TES" param="V0" id="2"
    tstart="0.02500001" tstop="100."
    start="10e-9" stop="10e-9"/>

</commands>
```



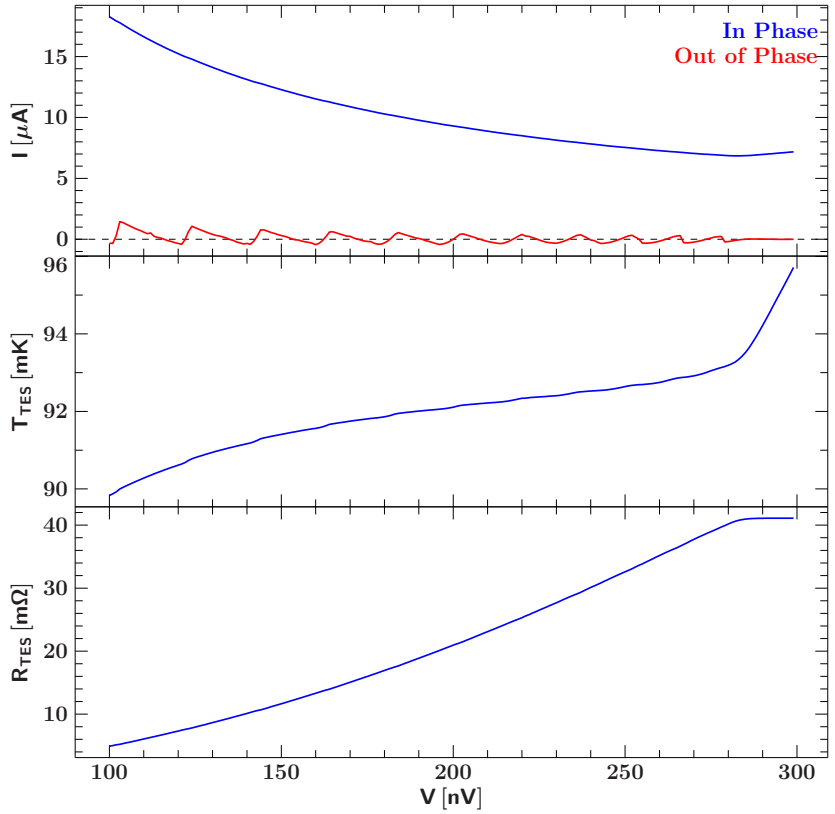

## Instrument Commanding

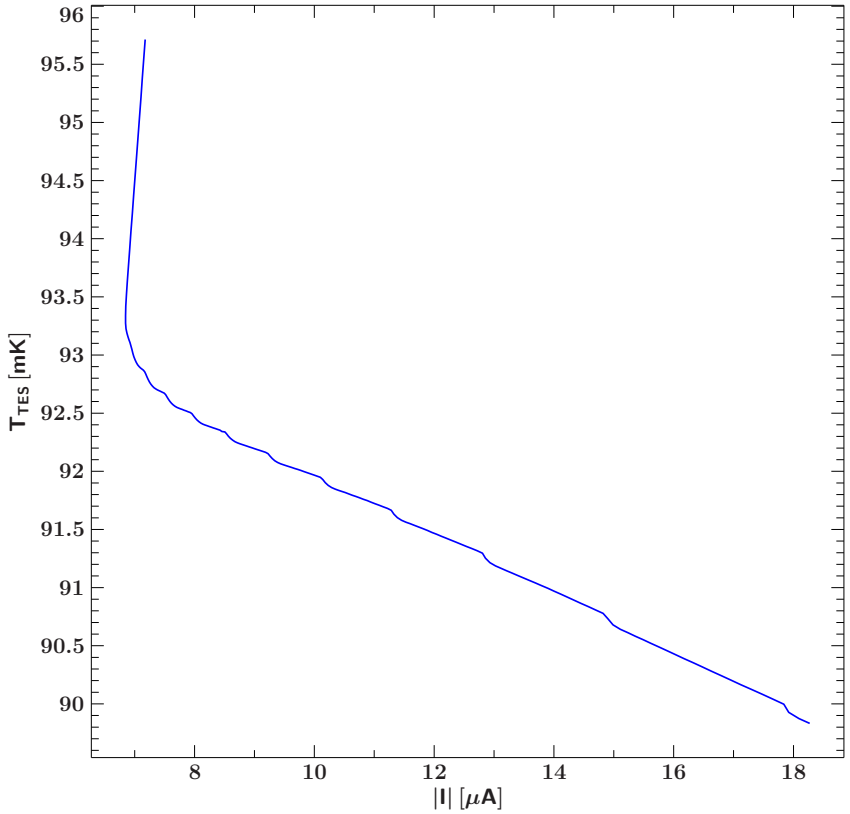
Using XML command interface, vary internal model parameters during the simulation

$\Longrightarrow$ Simulate calibration measurements, parameter drifts, crosstalk, . . .

# Examples – I-V curve

Example Calibration Measurement: I-V curve of a TES modelled as a Resistively Shunted Junction.



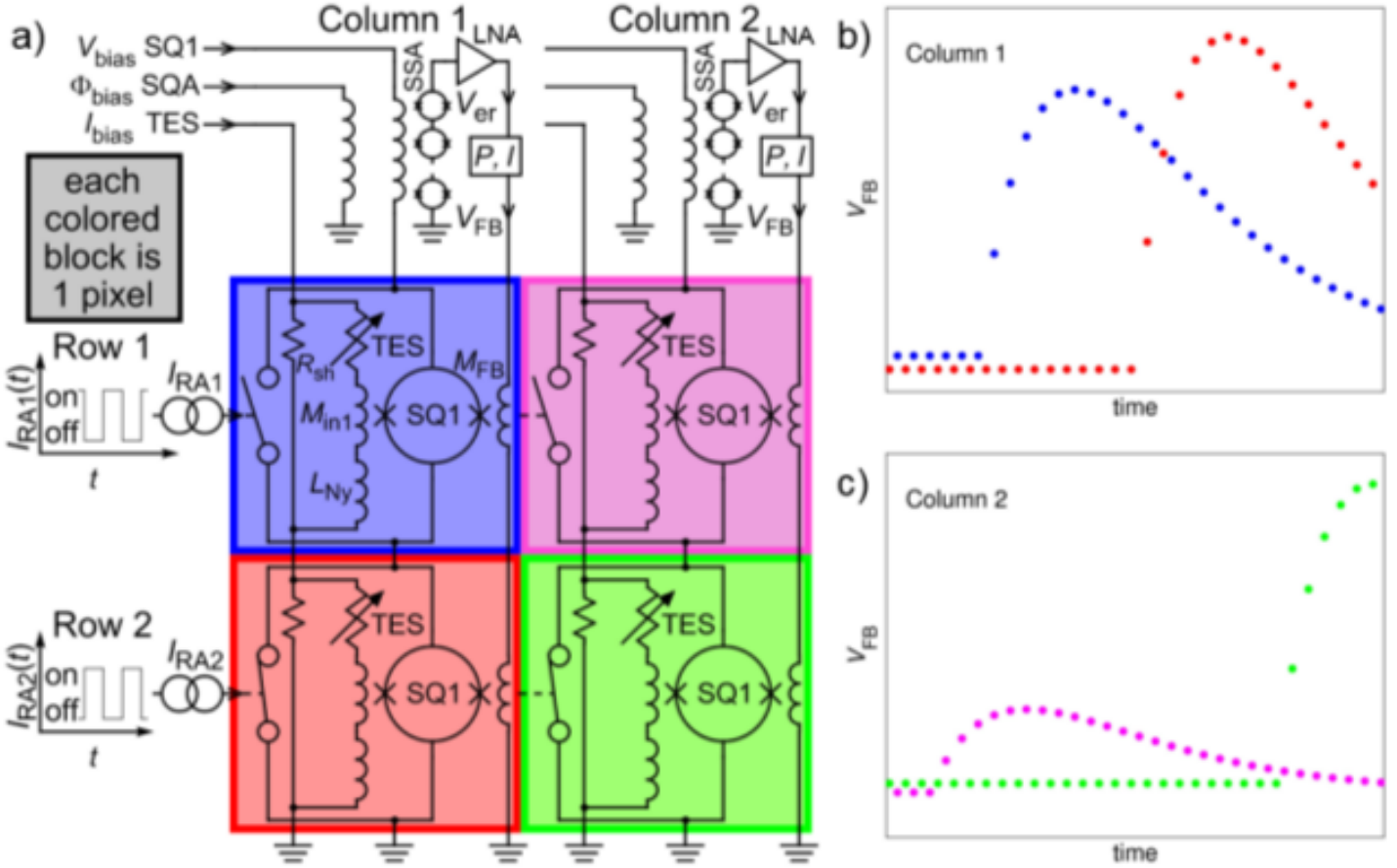

Typically, vary applied voltage and see current output. `xifusim` allows direct output of temperature and resistance, normally only indirectly accessible.

# Examples – TDM Switching Transients

Recall: TES readout is typically achieved via SQUID magnetometers followed by further amplifiers and digital readout

Due to large number of pixels (>3000), require use of multiplexing

Current baseline: Time-Division Multiplexing (TDM). Read out pixels in series at sampling rates much faster than pulse timescale.



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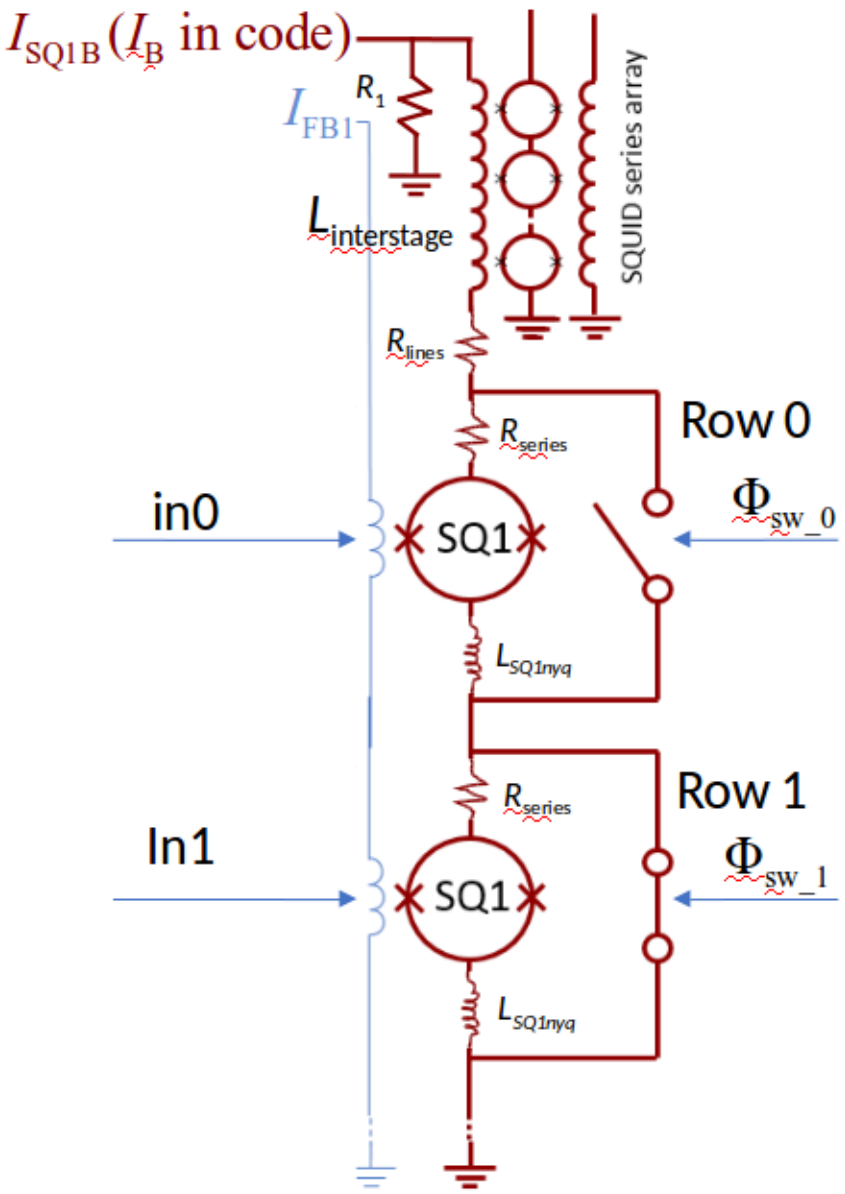
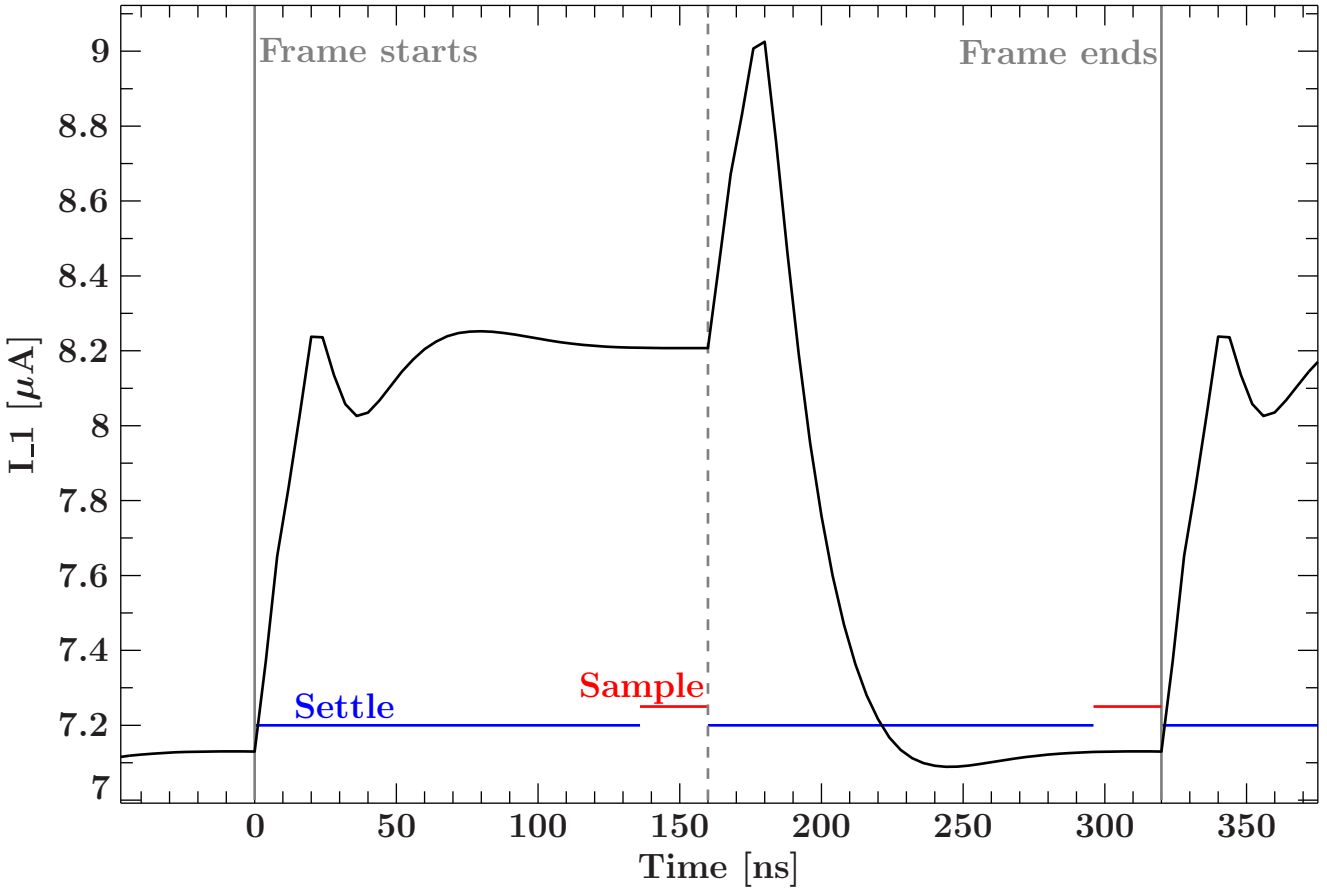



Model multiplexing stage in `xifusim` with representative circuit model and digital readout simulation.

Result: switching transients, as also seen in lab measurements:



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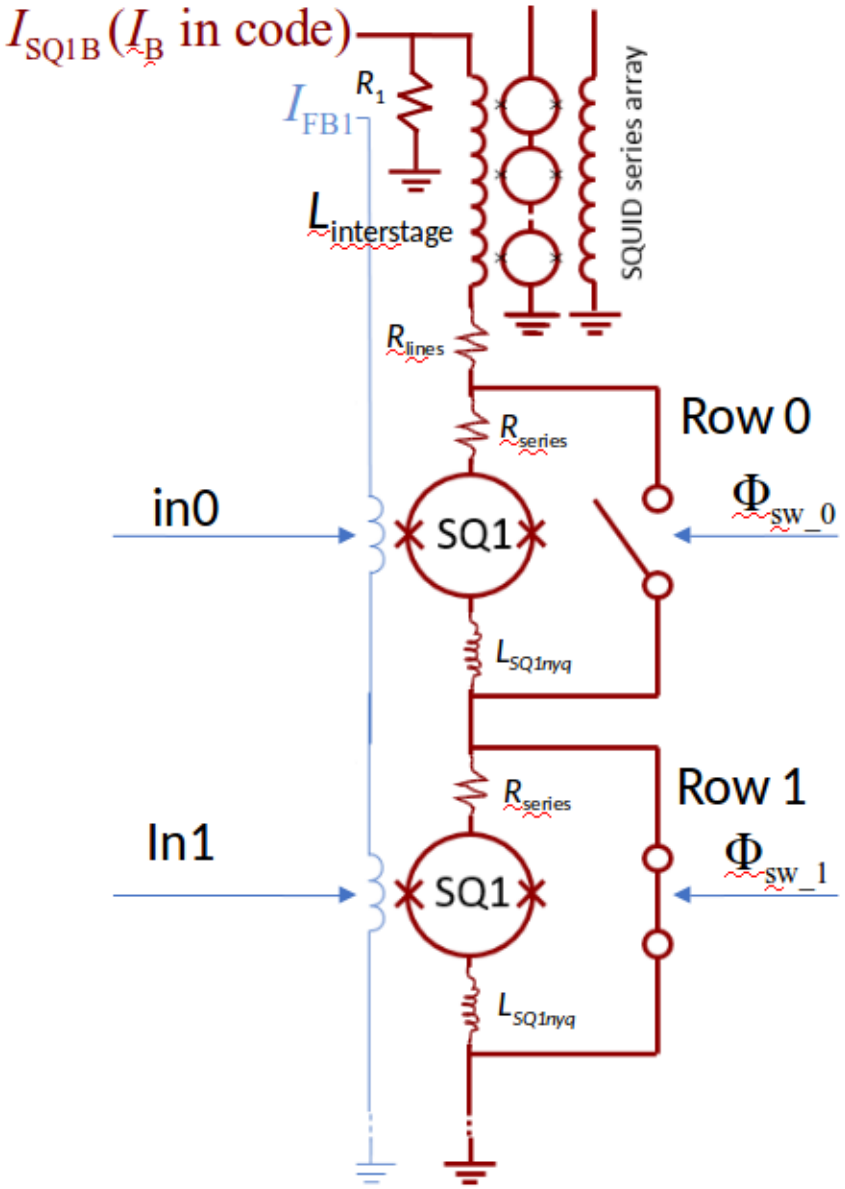
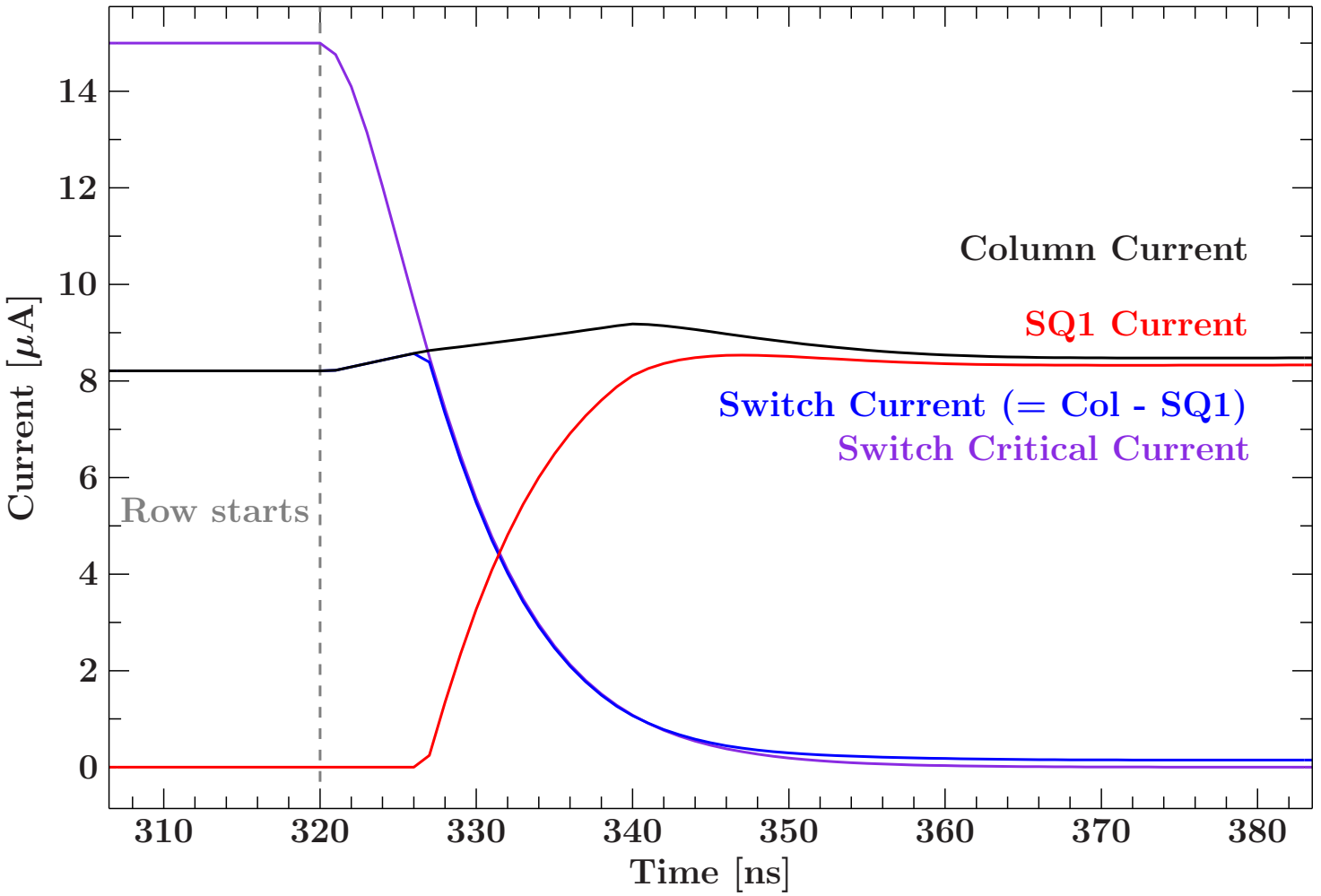



Internal state writing allows deeper look at generation of switching transients:

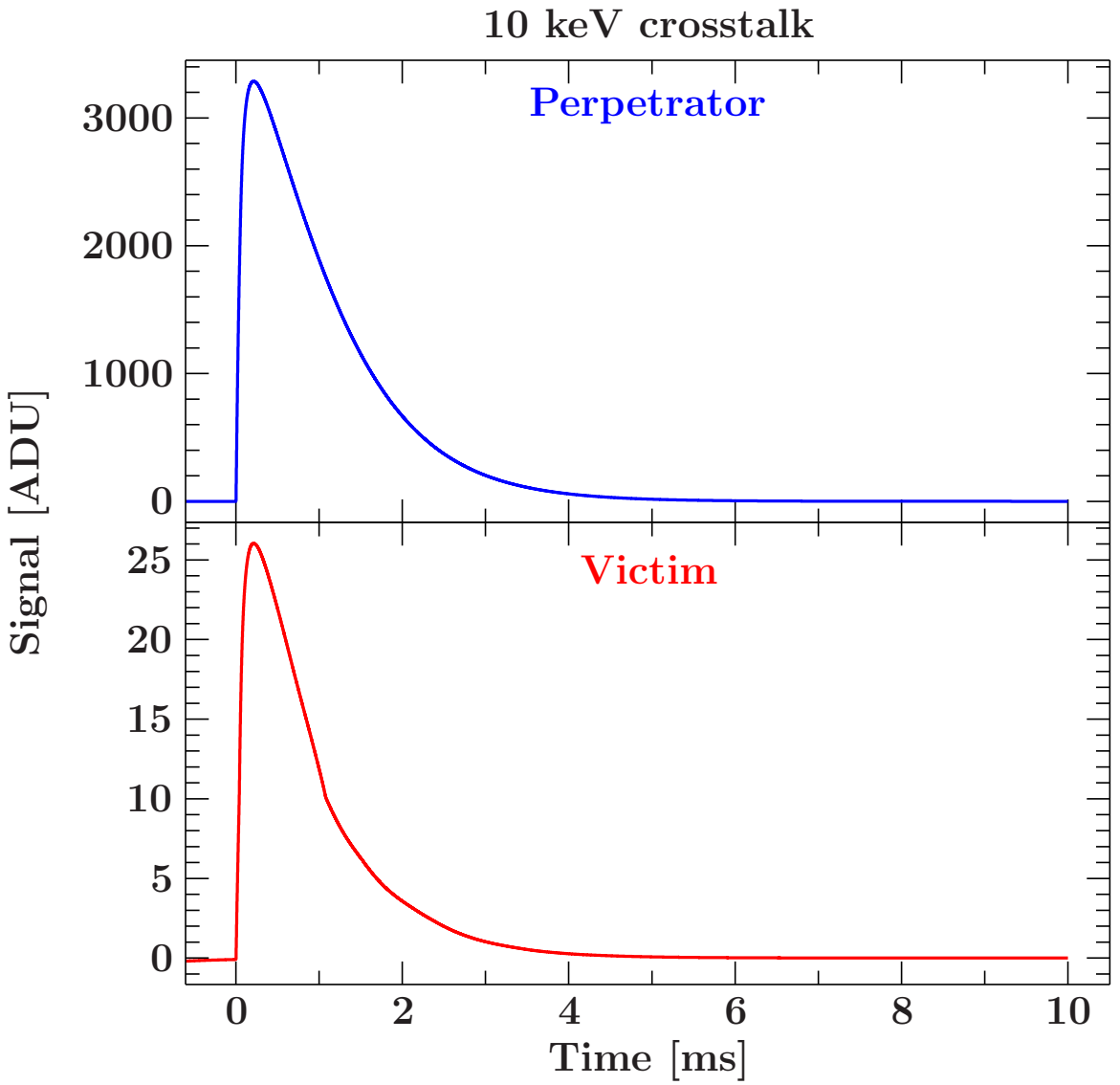


# Examples – TDM Crosstalk

Switching Transients are a form of signal leakage.
$\Longrightarrow$ Crosstalk! Photons in one pixel (perpetrator) cause signal in another (victim). Most noticeable as energy shift in victim pulse

`xifusim` can simulate crosstalk (this + other types) and provide Lookup Tables for SIXTE.

$\Longrightarrow$ Can study effect of crosstalk on observations!



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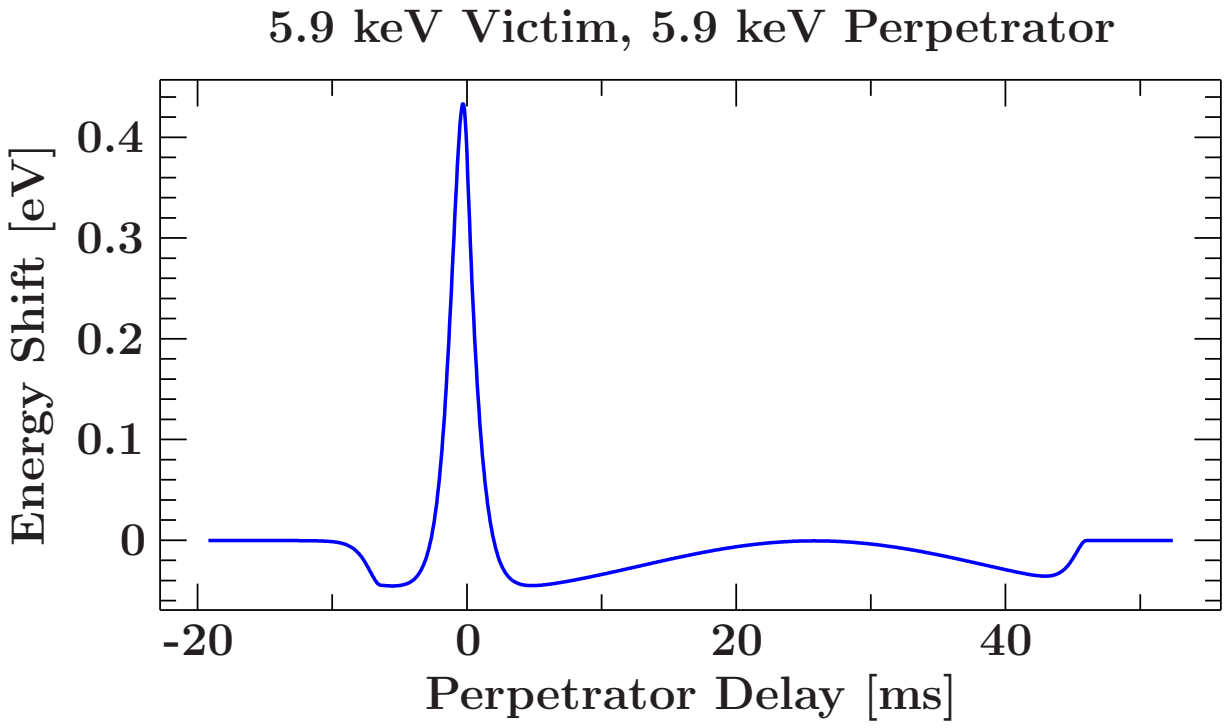

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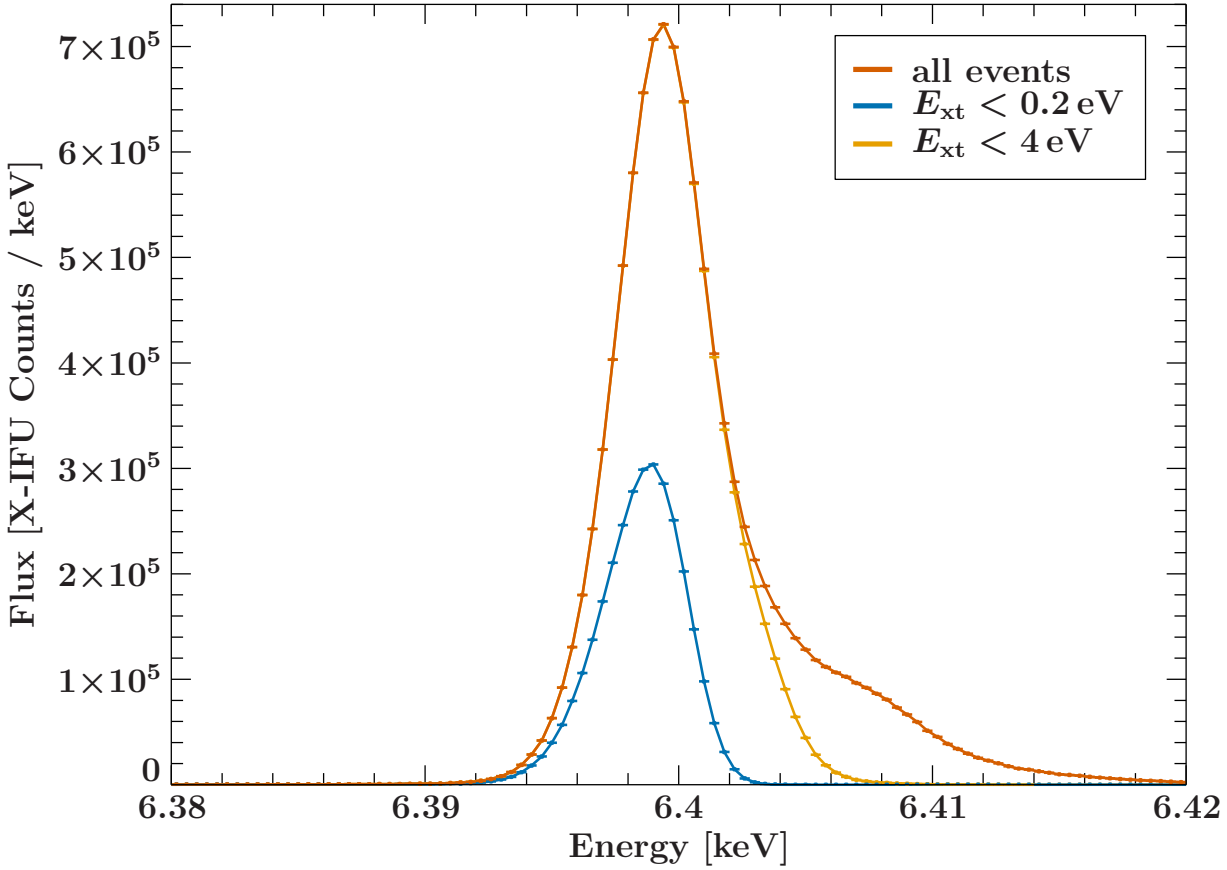

# Summary

`xifusim` is a simulator for a very ambitious mission, requiring extensive modelling. We achieve this via:

- Representation of the readout chain as a chain of modular blocks, adding models as needed
- Highly configurable output verbosity
- Commanding interface to allow non-standard simulations (more than photons only)

This allows us to use xifusim as both a standalone performance tool and a provider of input for higher level simulators, such as SIXTE.

**Thank you for your attention!**