End-To-End Simulations
X-ray Astronomical Example

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and many others

https://www.sternwarte.uni-erlangen.de/research/sixte/

What are End-to-End Simulations?

End-to-end (e2e) simulations: Simulation of the full detection chain for an astronomical instrument, from the astrophysical source through the imaging and detection process to the final data product.

$\Longrightarrow$ Full model of observational setup

E2e simulations have two major "customers":

Scientists:

- Gauge effect of design onto science: Can science goals be reached with the instrument?
  e.g., imaging quality, spectroscopy,. . .
- What other "observatory" science is possible?
- Plan future observations

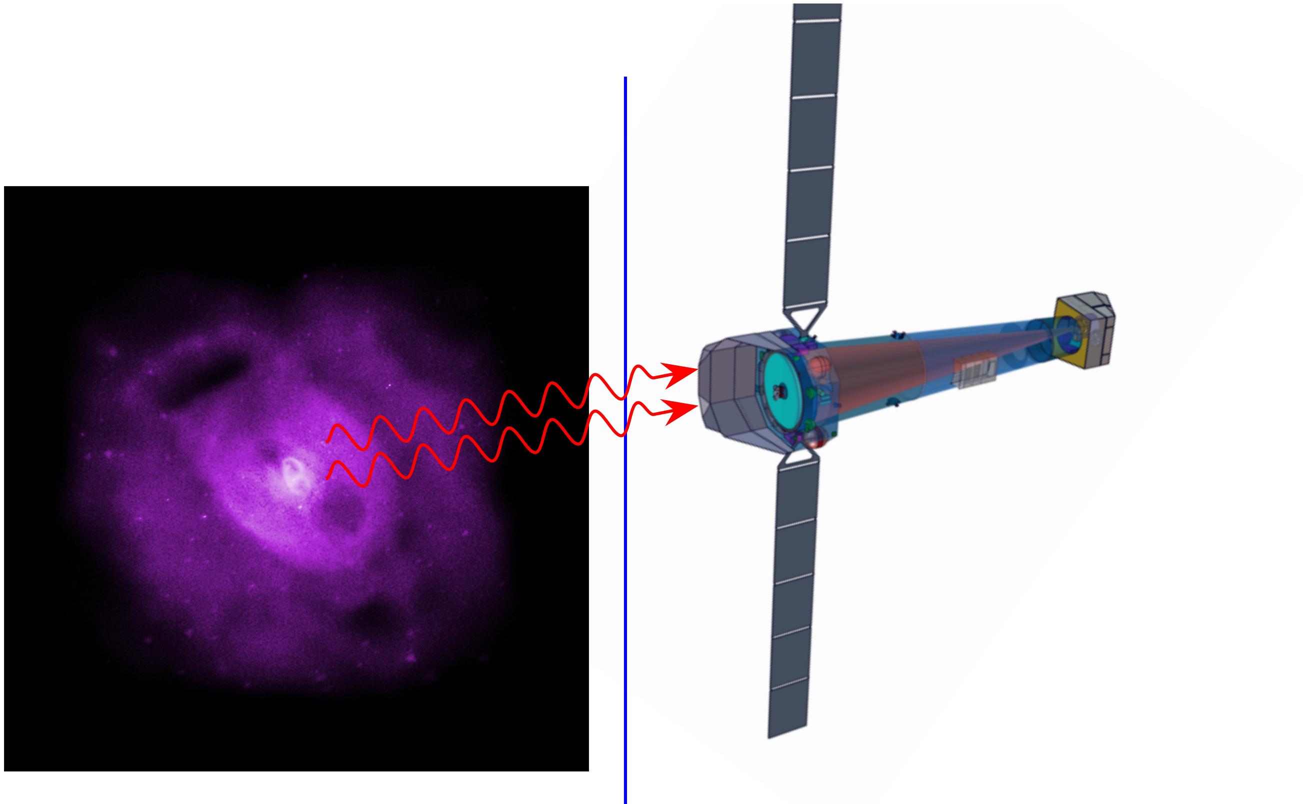
Instrumentalists:

- Use science examples to study design: What is impact of design onto science goals?
- Translation of instrument parameters $\Longleftrightarrow$ Science goals
- Estimate instrument performance
  e.g., telemetry constraints, CPU constraints

$\Longrightarrow$ Core component of mission design and implementation!

To be useful, e2e software should always represent best understanding of real instrumental performance.

Modeling



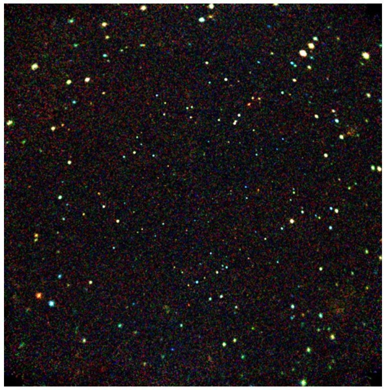
Source model – SIMPUT | Instrument model – SIXTE

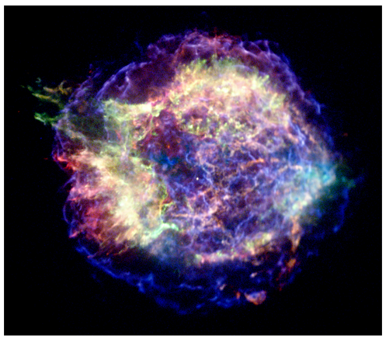
Source model: Define properties of the sources: Positions, Extended source/point source, spectral shape, variability,. . .

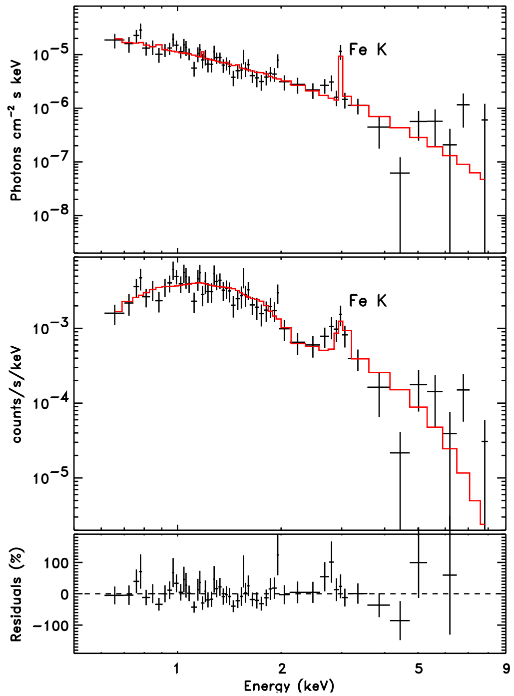
Instrument model: Define properties of the instrument: Imaging parameters, detection process, data processing chain

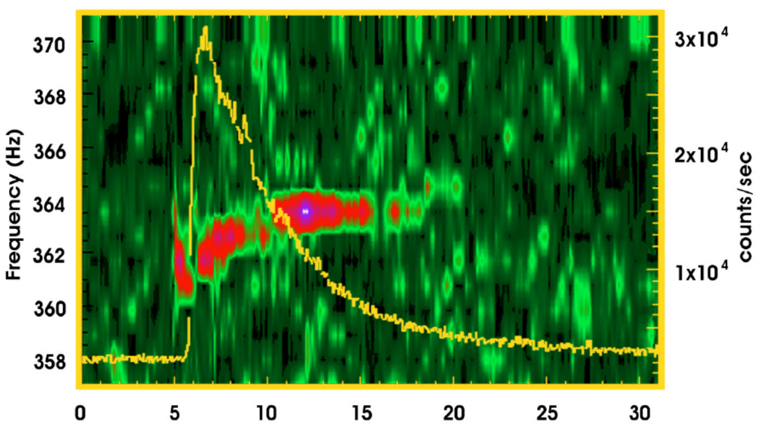
Output: Data that can be analyzed using standard astronomical analysis software (FTOOLS, XMM-SAS, XSPEC, ISIS,. . .)

Source Model: SIMPUT









sources are characterized by:

- source properties:
  - spectral shape
  - positions
  - light curves, pulse profiles, power spectra...
  - spatial extent
  - photon lists from MHD simulations
  - “data cubes” (e.g., cosmology)
- format allows reuse of common properties of sources

  e.g., reuse AGN spectra for multiple sources, reuse images of extended sources,...
- catalogs with arbitrary number of sources

  scales to millions of sources
- compatible w/other simulators

  `simx`, `MARX`

SIXTE

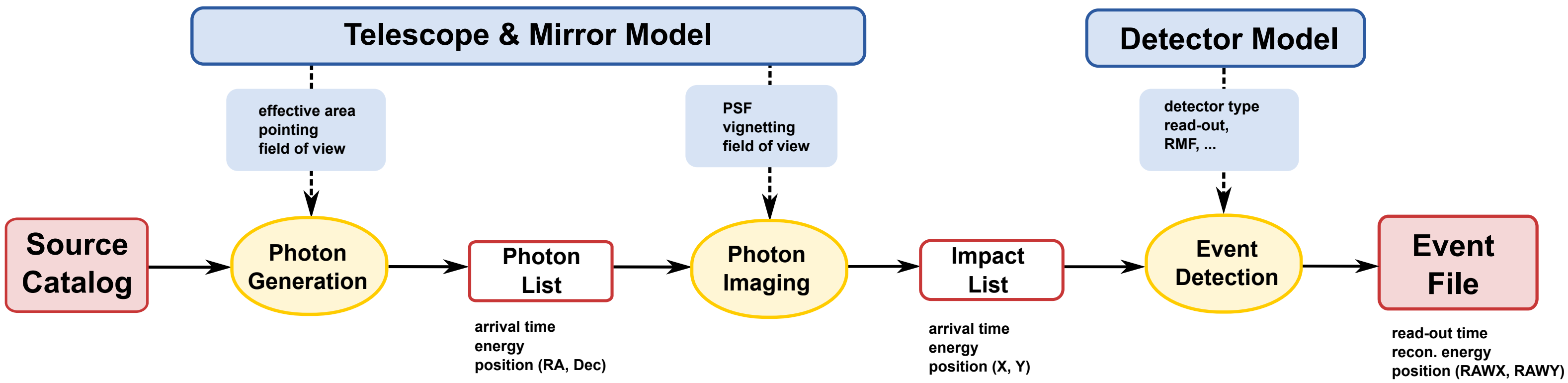
e2e environment: SIXTE, a generic Monte Carlo simulation framework for X-ray instruments (Athena, eROSITA, ARCUS, LOFT, XMM, Suzaku, LOFT,. . .)

http://www.sternwarte.uni-erlangen.de/research/sixte

- modular software → reuse existing algorithms for multiple instruments

  configuration files for Si-based X-ray detectors, calorimeters, X-ray gratings,. . . (can set up simulator for a mission with new parameters within few hours)

- command line driven for longevity



- utilizes calibration data (response files, PSF, . . .) *or* physics-based instrument model
- output: FITS event list (time, energy, pixel)

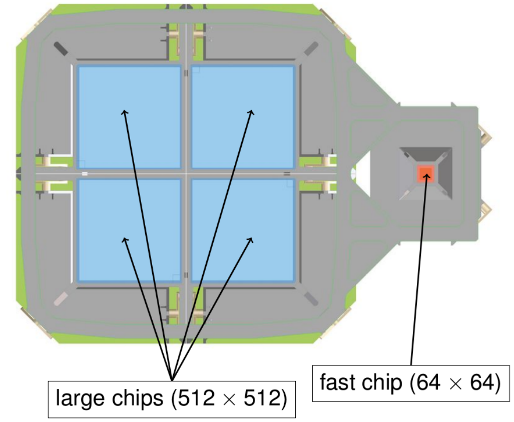
  format as close to real data as possible

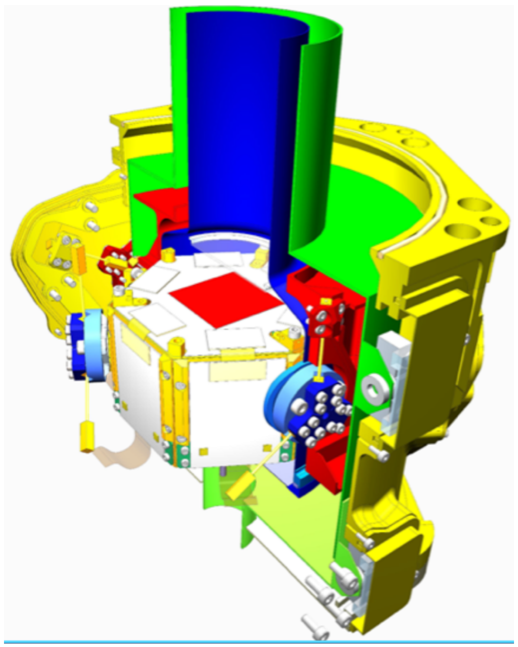
⟹ *one* simulator for science & technology development

Instrument model

- Imaging module
  - pointing
    (time dependent attitude, e.g., for dithering)
  - effective area
    (mirrors, filters, detectors,. . .)
  - vignetting
  - PSF
- Instrument module
  - two device simulators:
    - simple/fast simulation: response matrix sampling
    - advanced simulation: physics
      (e.g., $T(t)$ for X-IFU, photon effects in Si for WFI)

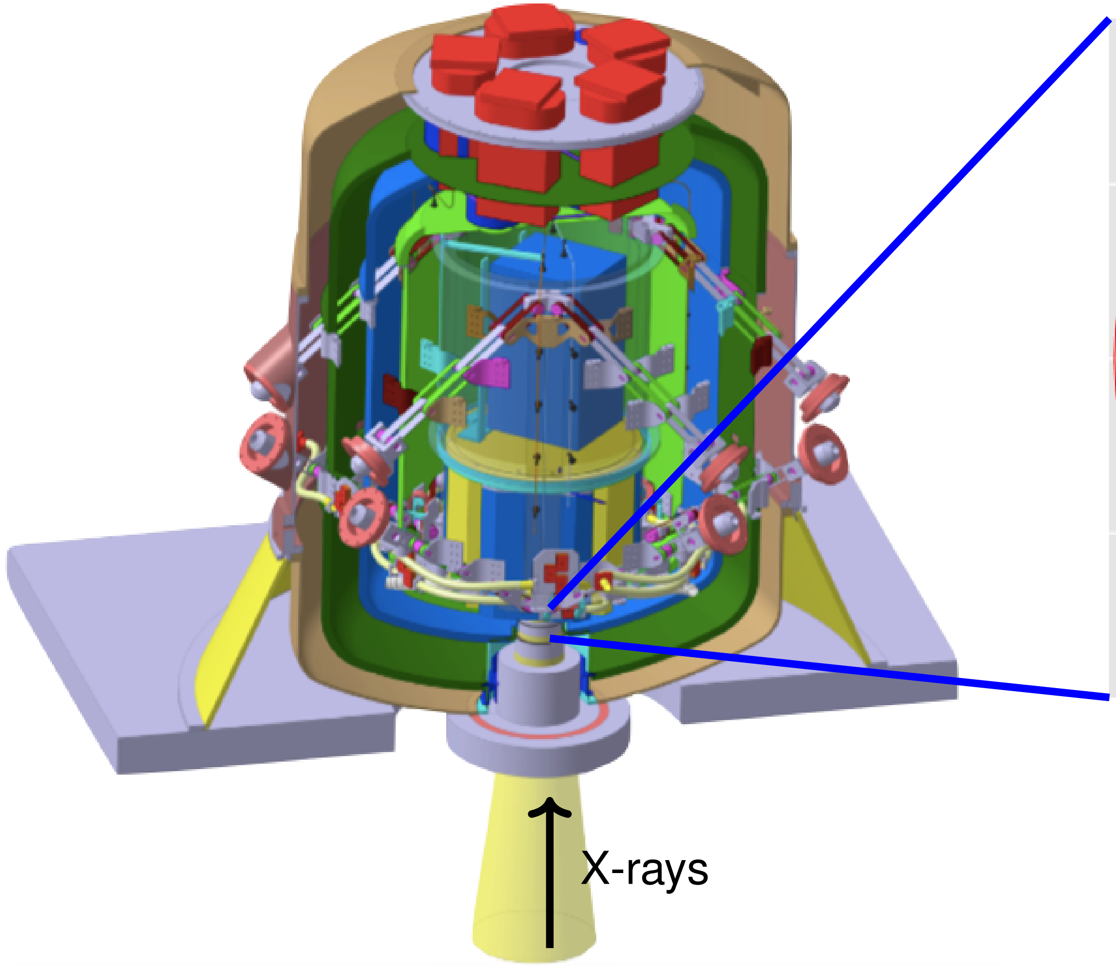
    flexible focal plane description (XML)
  - other effects considered: pile-up, crosstalk, background, readout
- Output: FITS event files

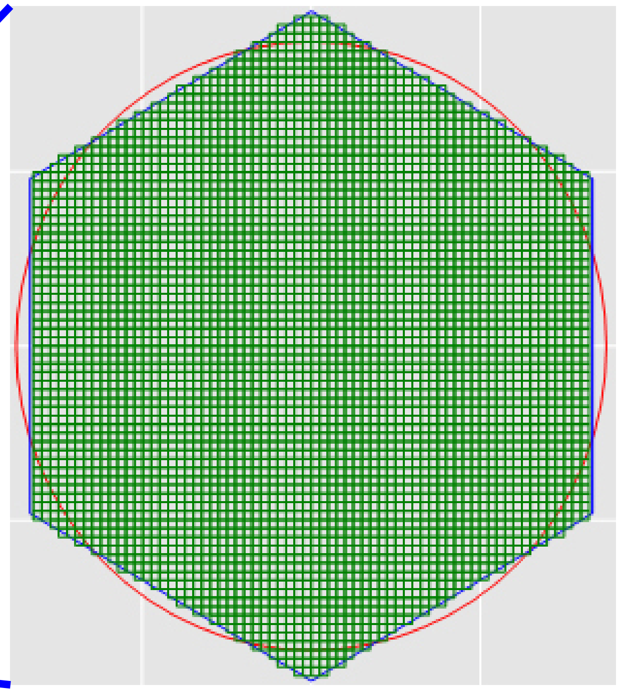




Example Instrument Model: X-IFU

The X-ray Integral Field Unit (X-IFU):

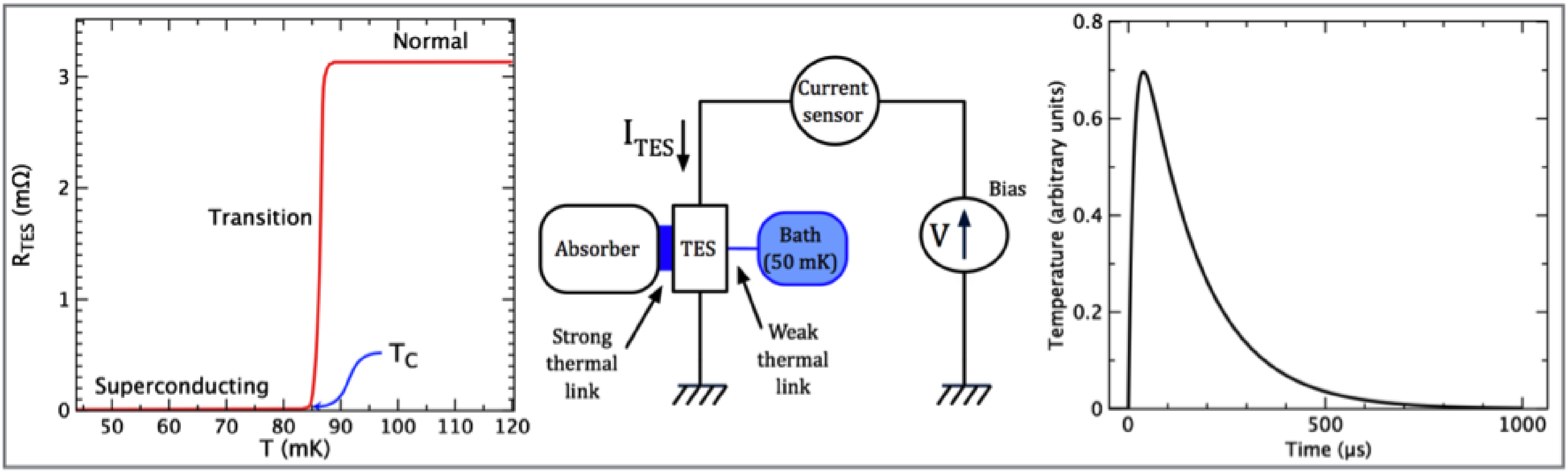




- 3148 TES (Transition Edge Sensor) pixels
- very high spectral resolution imaging (2.5 eV FWHM and a 5′ FoV)

X-IFU – Principle

X-IFU-pixels are single *Transition Edge Sensors*, operated at 50 mK ⇒ **measure temperature increase** of photon hitting the pixel



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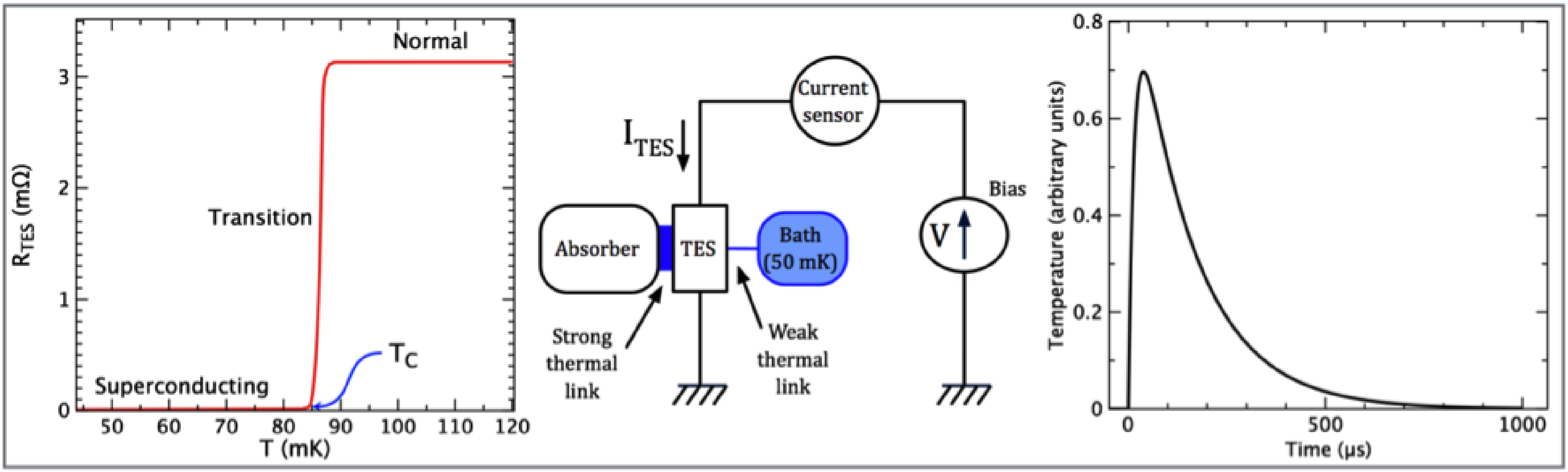

- SIXTE model: numerical solution of differential equations for $T(t)$, $I(t)$ (Irwin & Hilton, 2005),

$$C\frac{dT}{dt} = -P_\mathrm{b} + P_\mathrm{J} + P + \mathrm{Noise} \qquad \text{and} \qquad L\frac{dI}{dt} = V - IR_\mathrm{L} - IR(T,I) + \mathrm{Noise}$$

- linear resistance, $R(T, I; \alpha, \beta)$; noise: Johnson of circuit, bath, excess noise
- input parameters: C, G_b, n, α, β, m, R_0, T_0, T_b, L_crit (or a full model for the transition edge)

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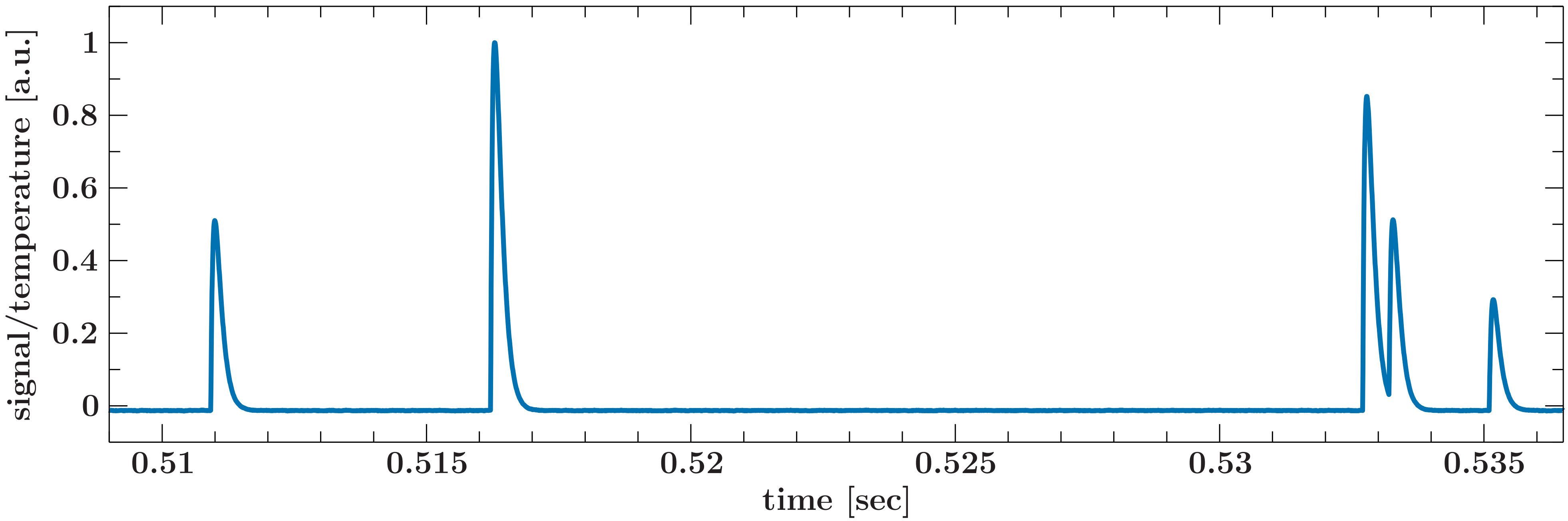
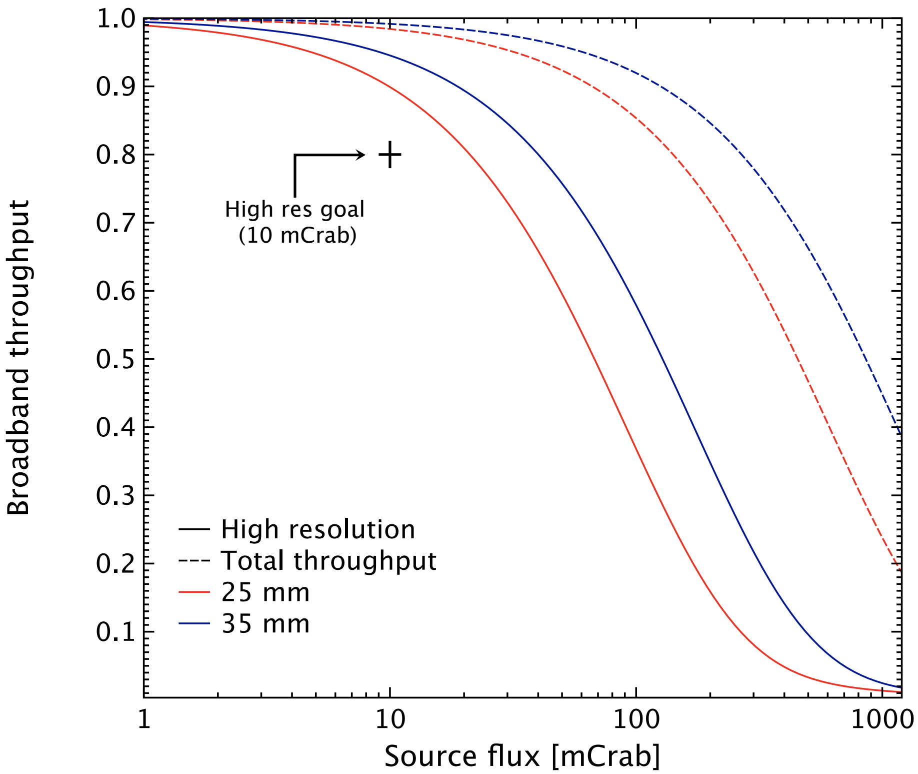
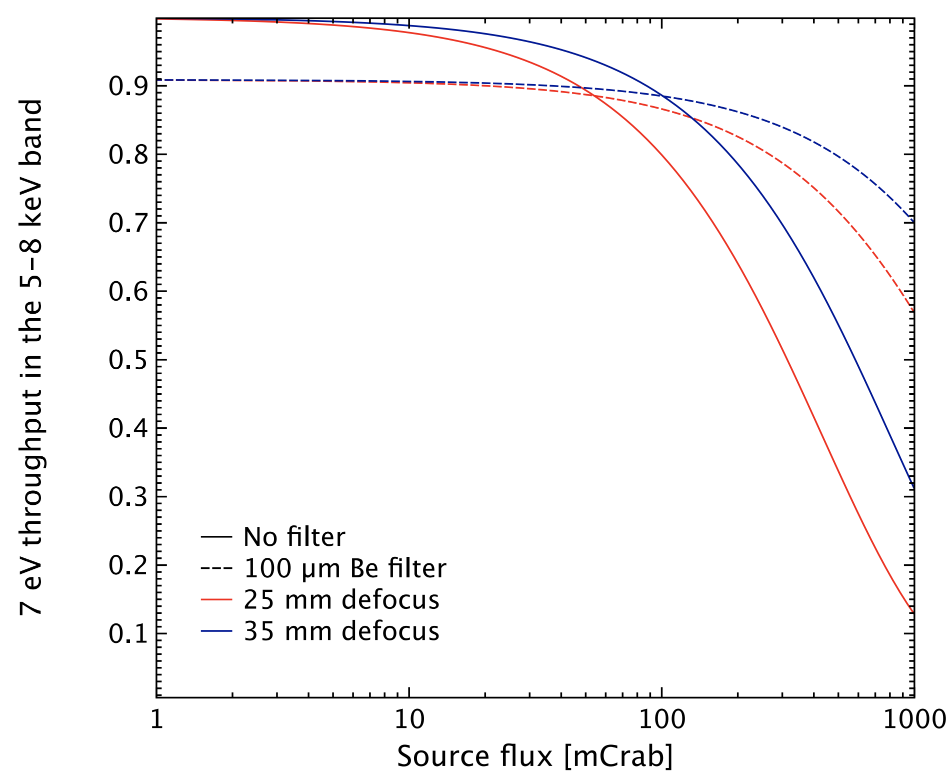


- pulse area ∼ photon energy
- pulses with smaller separation yield lower energy resolution
  ⇒ **Event Grading** depending on the source flux

X-IFU – Principle

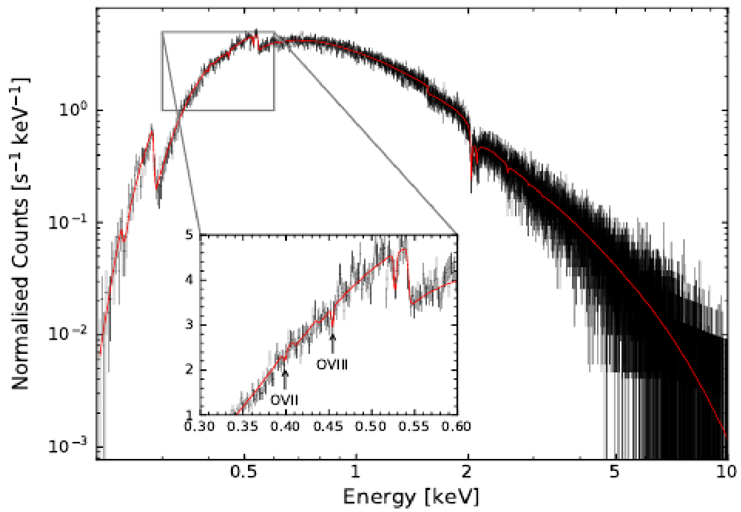
defocusing of the Athena optics allows observations up to 1 Crab

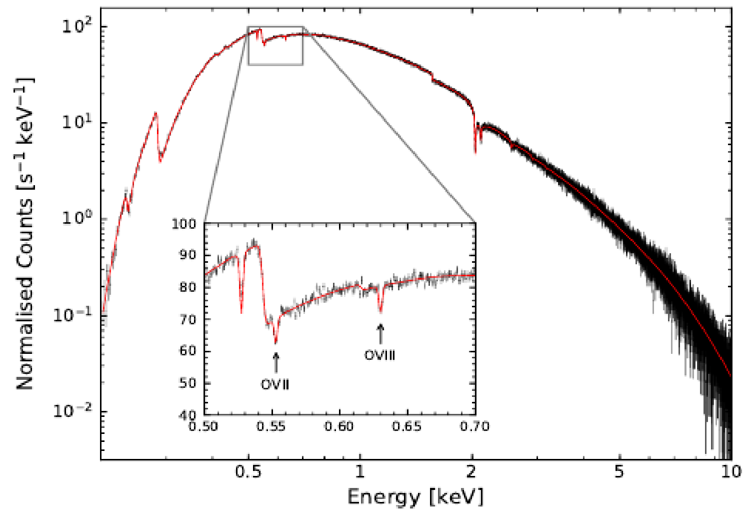




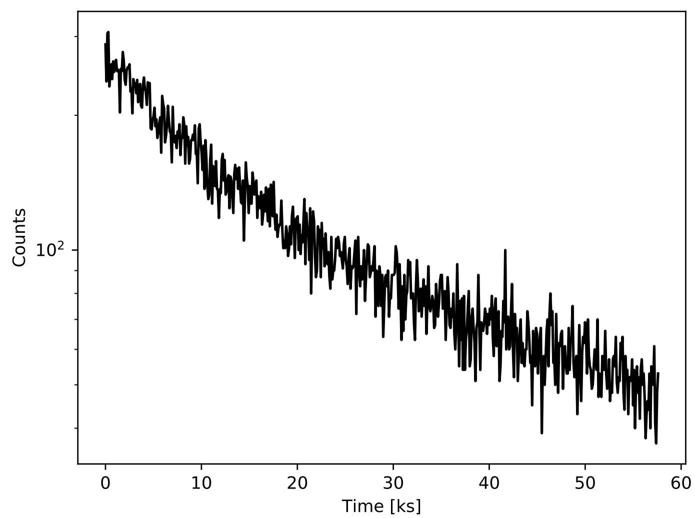
Grade	Δt since previous pulse	Δt until next pulse	Energy res.
(1) High res.	$\geqslant 7.9$ ms	$\geqslant 45.3$ ms	2.5 eV
(2) Medium res.	$\geqslant 7.9$ ms	$\geqslant 2.3$ ms	3 eV
(3) Limited res.	$\geqslant 7.9$ ms	$\geqslant 1.0$ ms	7 eV
(4) Low res.	$\geqslant 7.9$ ms	–	~ 30 eV

Example: GRBs and WHIM





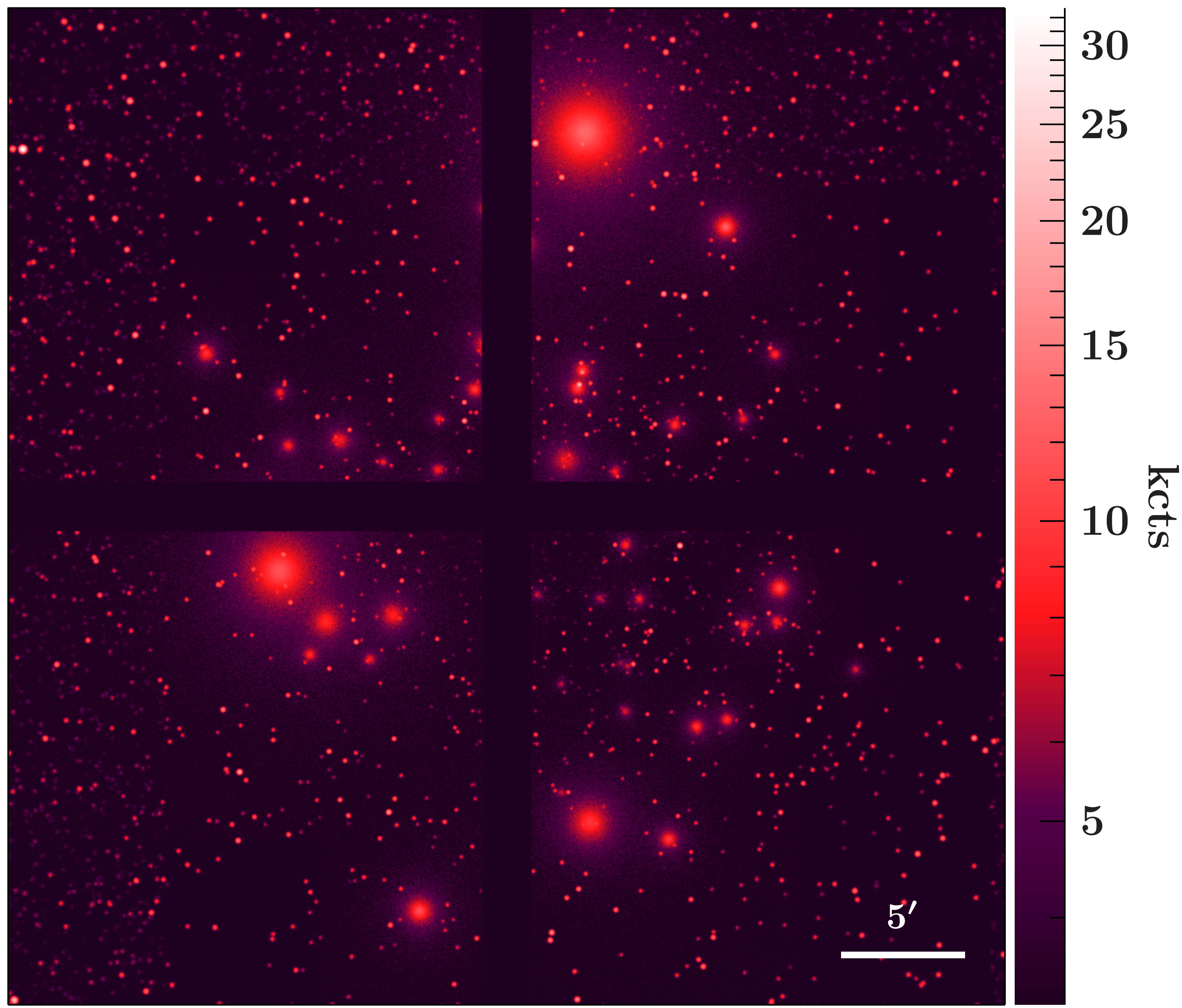
$z_{\mathrm{WHIM}} = 0.4388$ Walsh et al. (2020, A&A 642, 24; GRB is at z = 2) $z_{\mathrm{WHIM}} = 0.0382$



Example: Detection of Oxygen lines from WHIM in GRB spectra

Uses:

- realistic lightcurve
- realistic spectral shape



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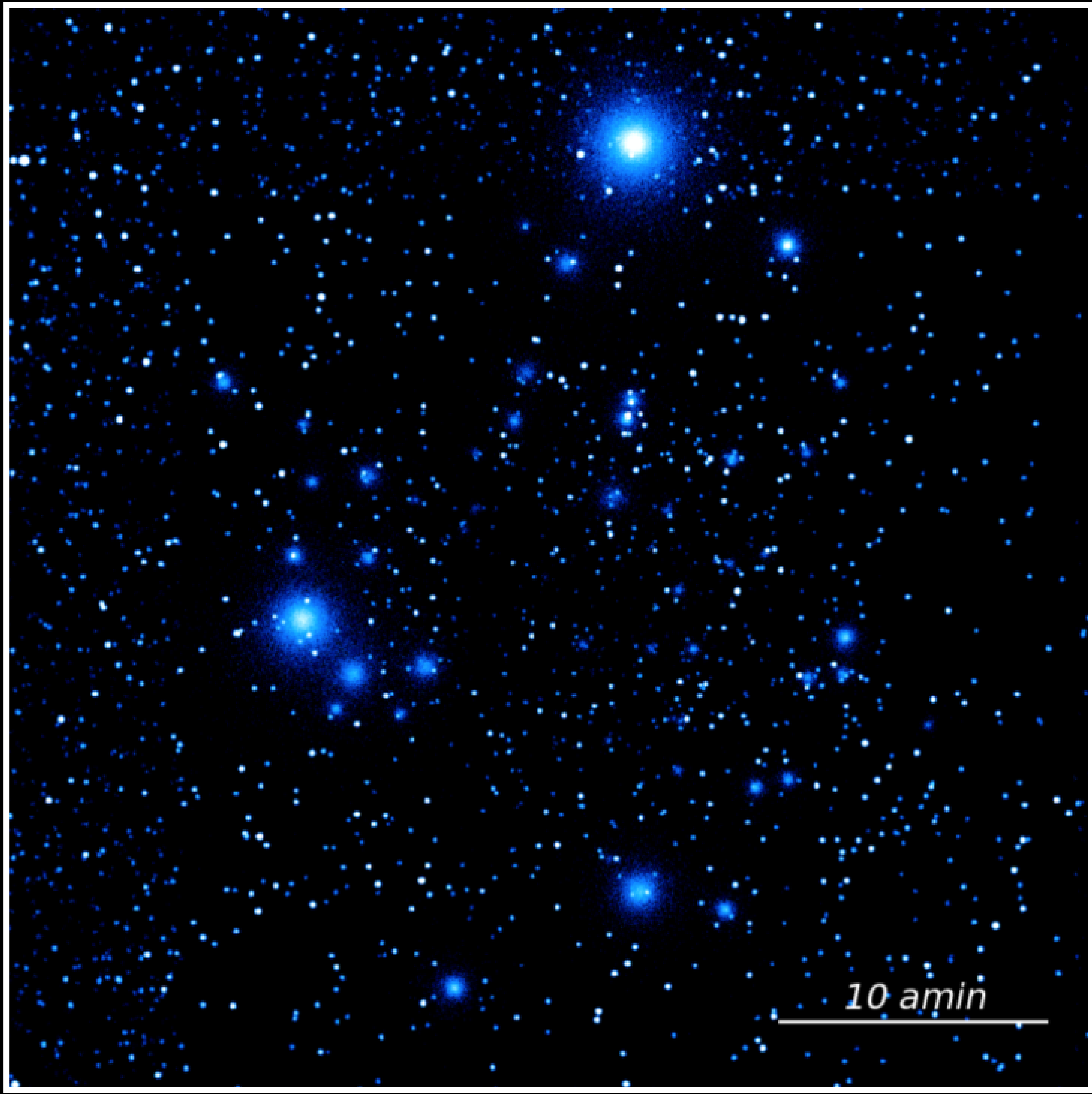
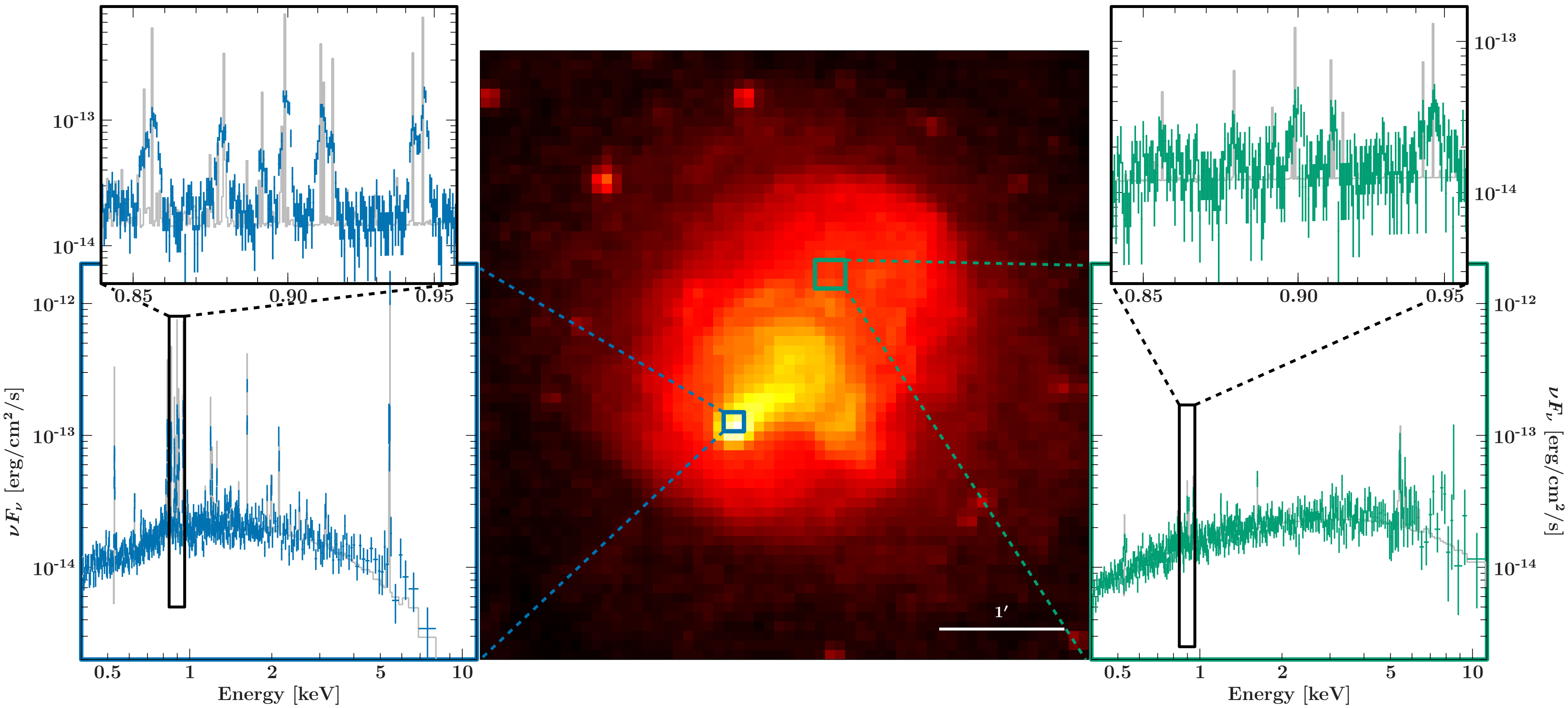


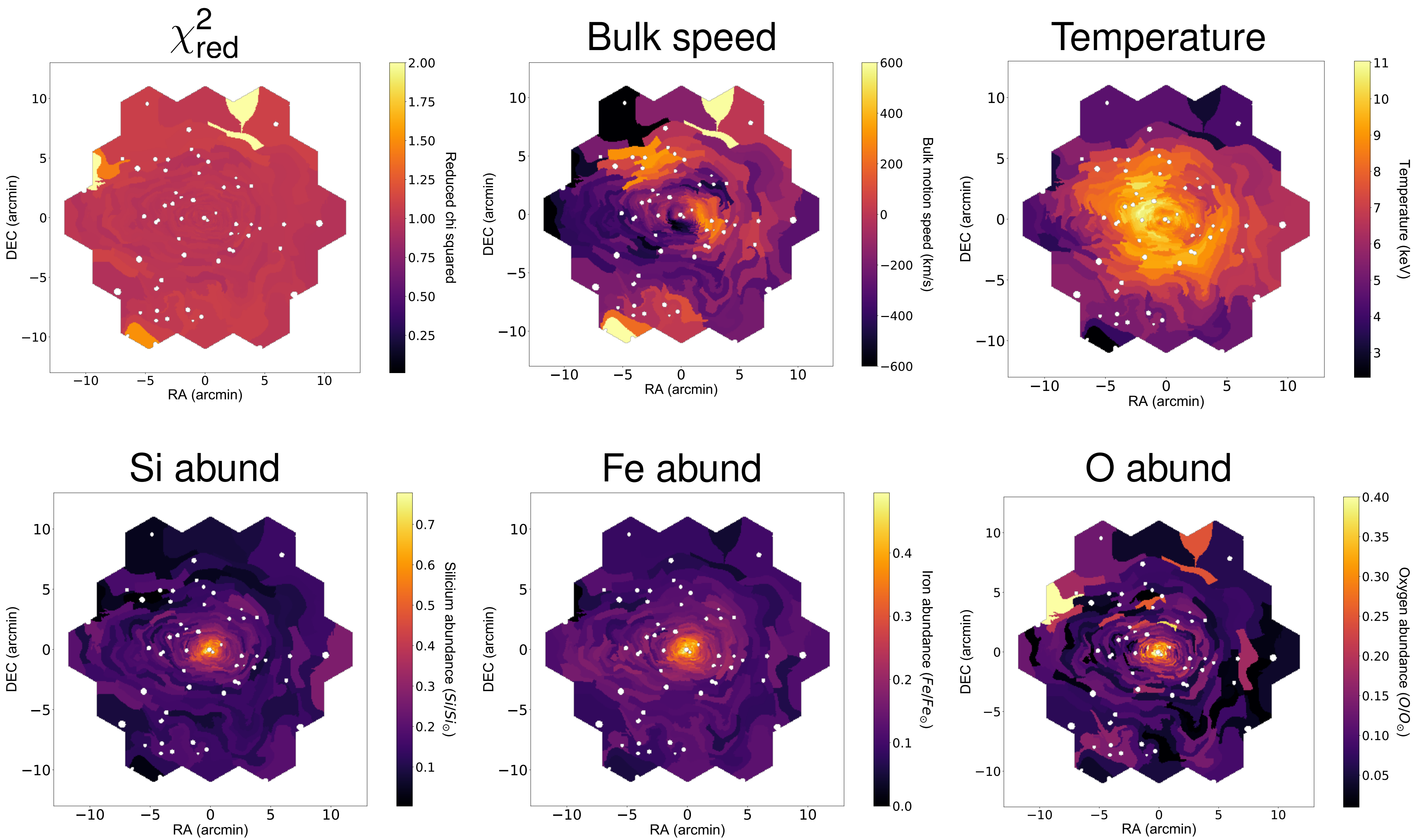
Dithering efficiently removes the chip gaps

Example: Galaxy clusters



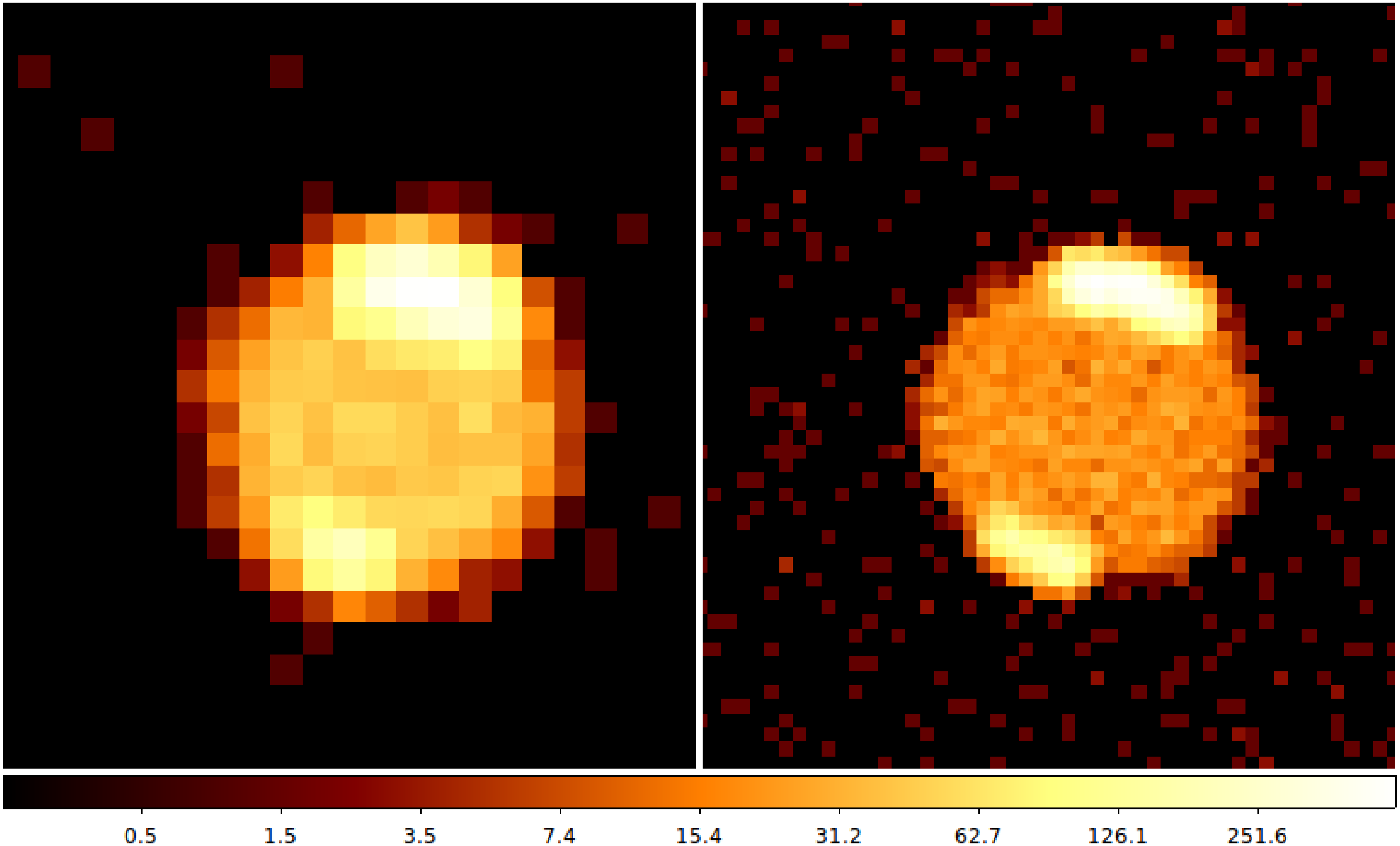
Abell 2146 with X-IFU (T. Dauser/E. Pointecouteau)

Example: Galaxy clusters



after E. Cucchetti et al. (2018, A&A 620, 173)

Example: Jupiter



Jupiter in the WFI and the X-IFU (C. Kirsch / G. Branduardi-Raymont)

Summary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SIXTE | Installation | Examples | Athena | SIMPUT | Contact

SIXTE - Simulation of X-ray Telescopes

SIXTE is a software package for X-ray telescope observation simulations developed at the Remeis Observatory (ECAP). It allows to undertake instrument performance analyses and to produce simulated event files for mission- and analysis studies.

The software strives to find a compromise between exactness of the simulation and speed. For many cases, by using calibration files such as the PSF, RMF and ARF, efficient simulations are possible at comparably high speed, even though they include nonlinear effects such as pileup. Setups for some current and future missions such as XMM-Newton or Athena are included in the package, others can be added by the user with relatively little effort through specifying the main instrument characteristics in a flexible, human-readable XML-based format.

For an overview of the SIXTE software package, see Dauser et al. (2019). If you use results obtained with SIXTE in a publication, please cite as: "This research has made use of the SIXTE software package (Dauser et al., 2019) provided by ECAP/Remeis observatory (https://github.com/thdauser/sixte)."

SIMPUT Format - Source Description

Properties of X-ray sources to be simulated are described in a detector-independent format, i.e., the same input can be used for simulating observations with all available instruments, and the same input can also be used for simulations with the SIMX simulator. The input files can be easily generated from standard data such as XSPEC spectral models or FITS images with tools provided with the SIXTE distribution. The input data scale well from single point sources up to very complicated setups. For example, for ATHENA we have simulated observations of the galactic center based on the Chandra input catalogues and images of the diffuse emission, while for eROSITA we regularly perform simulations of the whole sky using several million time-variable point sources.

More details on the SIMPUT format are described here. We also provide selected SIMPUT files for download, which can be readily used in a Sixte simulations.

SIXTE Simulator Manual

The first version of the SIXTE simulator manual is available for download below. It includes general description of SIXTE and the implementation of detectors such as the WFI, X-IFU, eROSITA and others. In addition, tutorials for Athena WFI and X-IFU simulations are included.

download: simulator_manual.pdf (v1.3.10, 2019-11-15)

supplementary files for the X-IFU tutorial (30MB!): X-IFU_clusters_tutorial.tgz

4 year eROSITA Attitude file for a launch in April 2019 (200MB!): eRASS_4yr_epc85_att.fits.bz2

4th SIXTE Workshop (19.-21. February 2019, IFCA)

On the 19. until 21. February 2019 the fourth SIXTE workshop took place in Santander, with a focus on Athena WFI and X-IFU simulations. Below is a selection of the talks presented there.

Access:

- documentation: 96 p. manual and Dauser et al. (2019, A&A 630, 66)
- help desk: sixte-support@lists.fau.de
- Source code: `http://www.sternwarte.uni-erlangen.de/research/sixte`.

  Works on Linux and Mac, git and release versions; also available on JHU sciserver