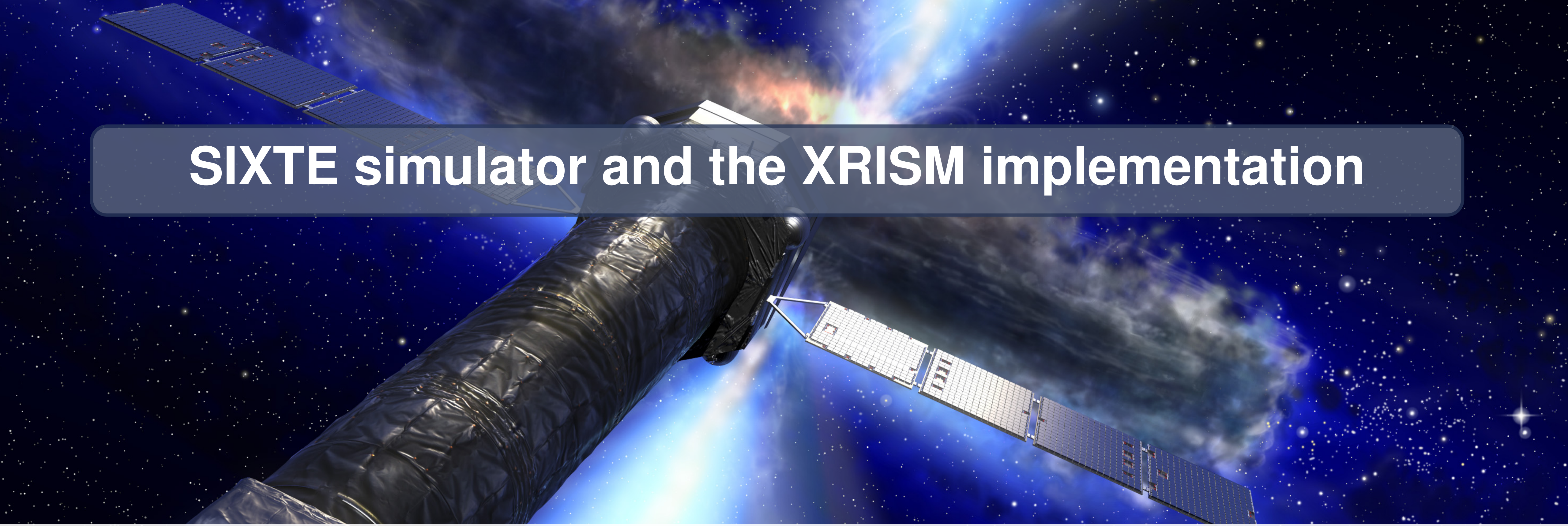
SIXTE simulator and the XRISM implementation



Jörn Wilms on behalf of the SIXTE team

Remeis Observatory & ECAP

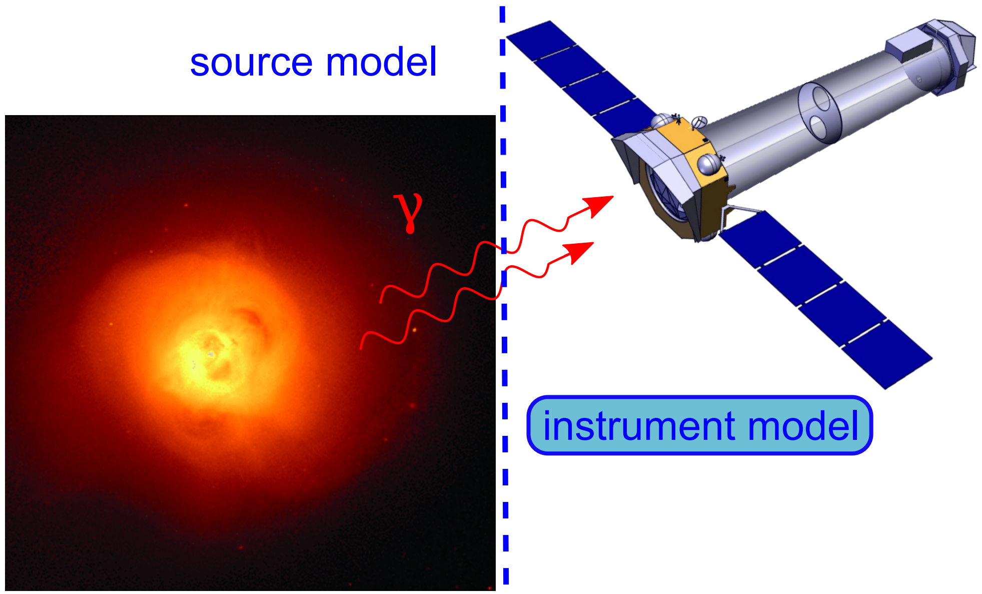
L. Dauner, T. Dauser, C. Kirsch, M. Lorenz, N. Reinmann (ECAP),
E. Cucchetti, P. Peille (CNES), M. Ceballos, B. Cobo (IFCA), and many others

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

3rd XRISM community workshop, College Park, 2025-02-05

SIXTE Introduction

SIXTE Overview



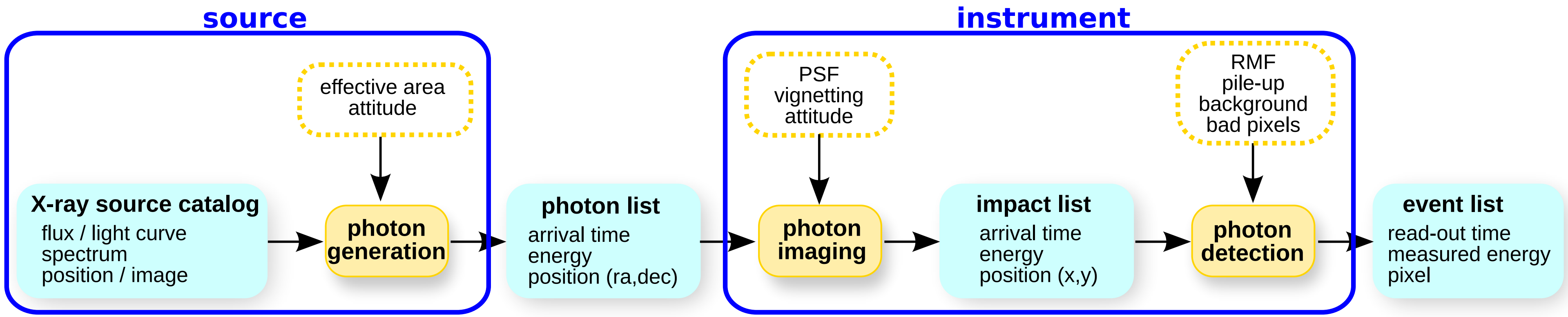
SImulation of X-ray TElescopes

SIXTE simulates the full detection chain from the astro-physical source through imaging and detection.

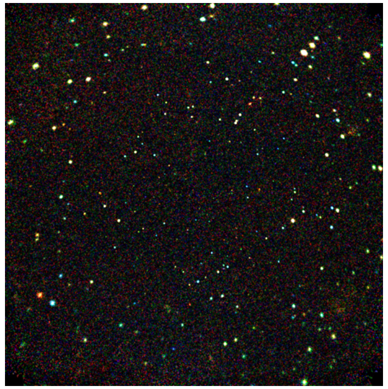
The simulation output are standard FITS files.

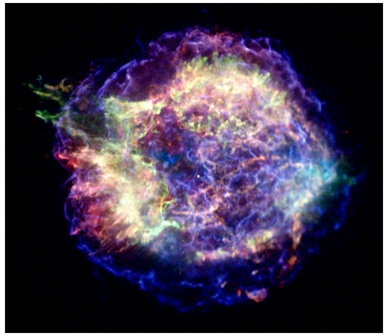
Tools for image creations, spectral extraction, exposure maps and ARF generation are provided as part of SIXTE.

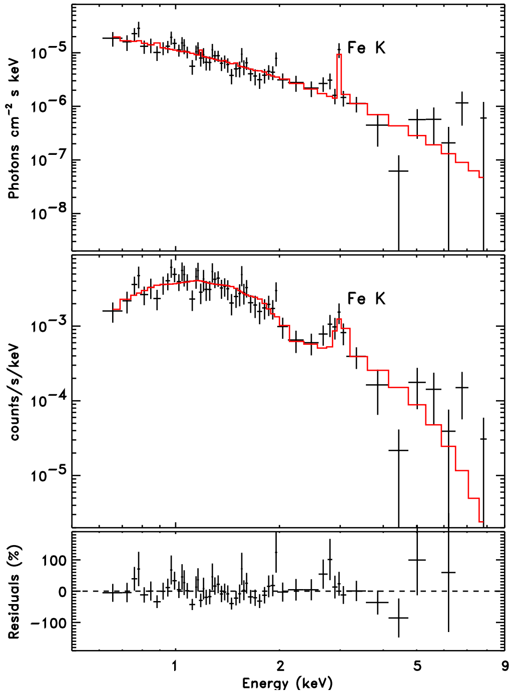
Note: Source and instrument models are separate. Source definitions can be re-used for any instrument!

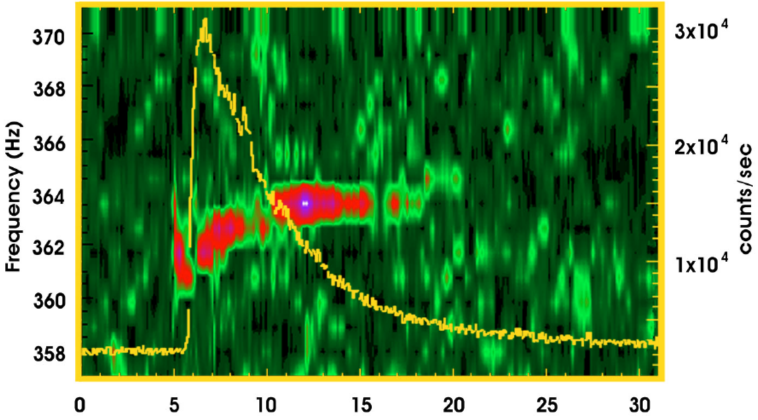


SIMPUT Format









Sources are characterized by:

- position: (α, δ)
- spectral shape: $F(E)$
- flux distribution: $F(\alpha, \delta, E)$
- variability: $F(\alpha, \delta, t, E)$
- foreground absorption: $N_{\mathrm{H}}(\alpha, \delta)$

Features:

- try to be as close as possible to reality, no artificial limitations on source spectral shape, images, etc.
- make catalogs of SIMPUTs, scales up to millions of sources by reusing spectra
- compatible w/other simulators (`simx`, `MARX`)

Detector Modeling

Detector Models

Detector modeling in SIXTE tries to achieve a balance: Sufficient detail to be representative, but still able to run long simulations on Laptop-like resources

SIXTE is already used for many current and future missions, such as *eROSITA*, *Athena* X-IFU and WFI, *THESEUS*, *AXIS*,. . .

Based on this heritage, we have models to simulate *XRISM*:

Resolve

Microcalorimeter model with grading and crosstalk (and PSP limits in process)

Xtend

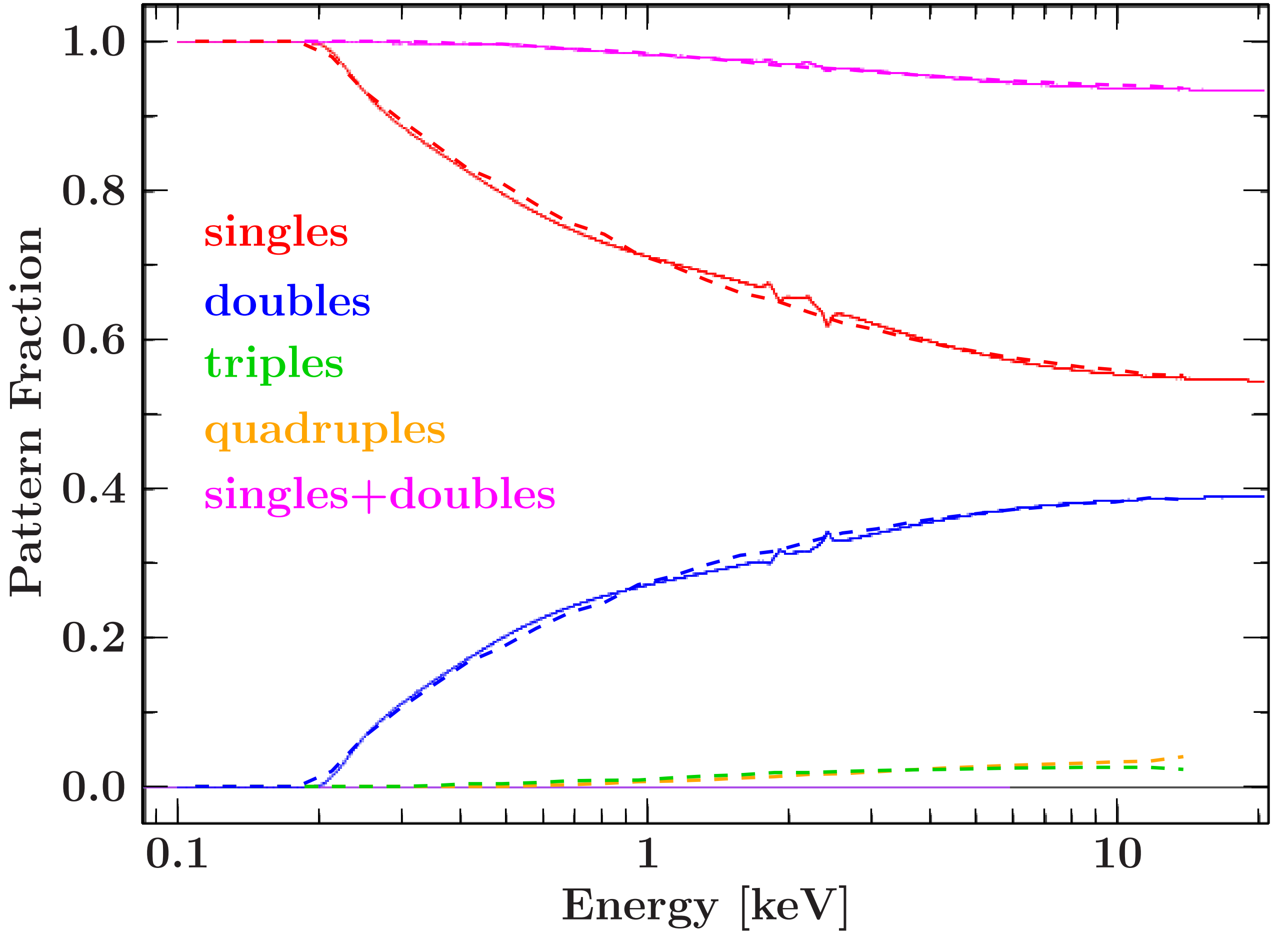
CCD model with multiple detectors and readout modes

CCD Effects – Patterns and Pileup

In CCD (or generally semiconductor) detectors, SIXTE models the spread of photon signals over multiple pixels via a charge cloud model.

Based on a photon's impact position and energy, a frame contains different event patterns.

Example:
Reconstruction of pattern fractions in EPIC pn on *XMM Newton* (solid lines) with SIXTE (dashed lines)



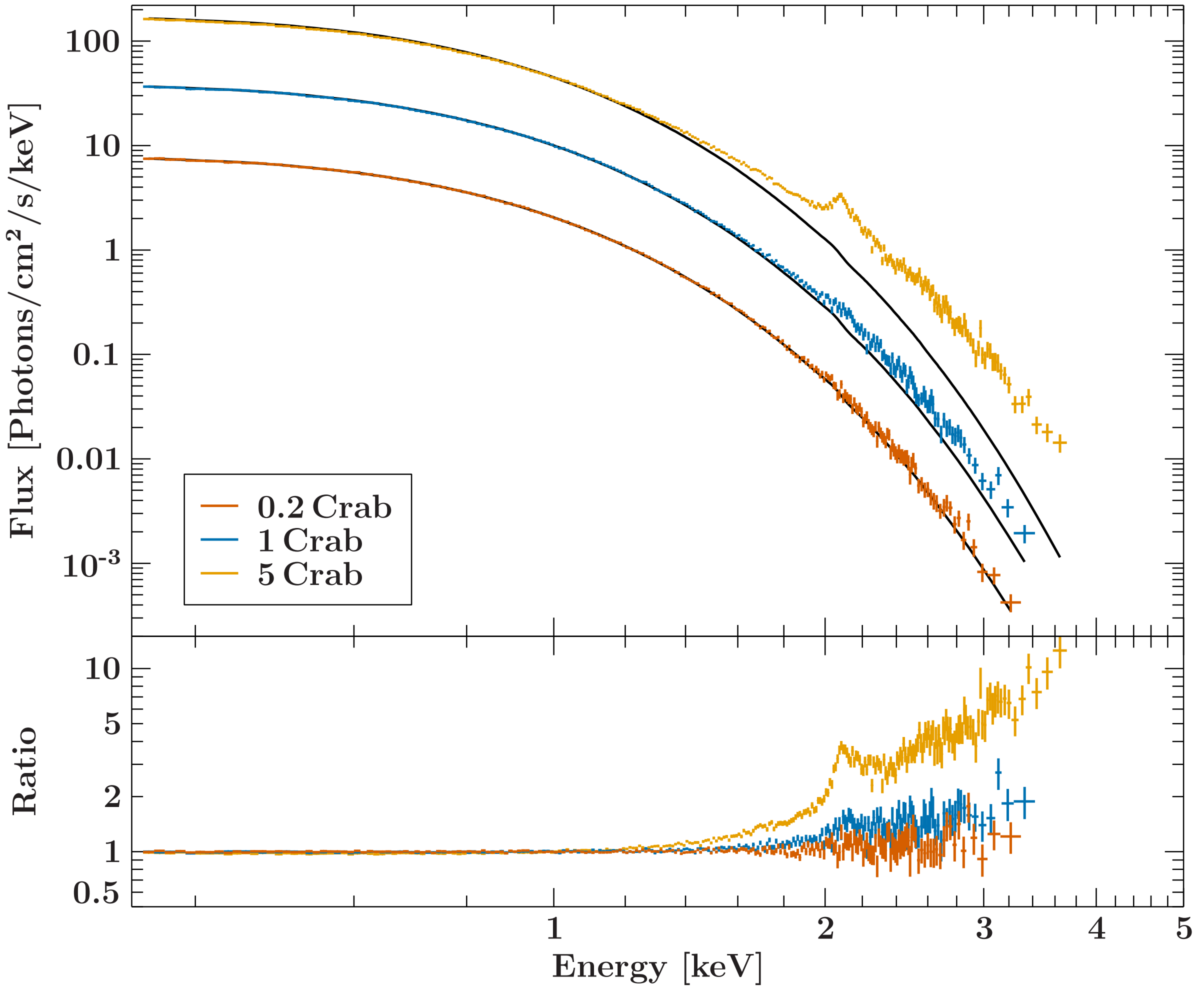
Dauser et al. (2019)

CCD Effects – Patterns and Pileup

In CCD (or generally semiconductor) detectors, SIXTE models the spread of photon signals over multiple pixels via a charge cloud model.

At high count rates, multiple photons may hit the same pixel within the same frame, or form a fake, valid looking pattern. This is called pileup and leads to a distortion of the spectrum.

Example: *Athena* WFI fast detector simulation of a 200 eV black-body at various fluxes. At high flux, the spectral shape (black, solid) is distorted.



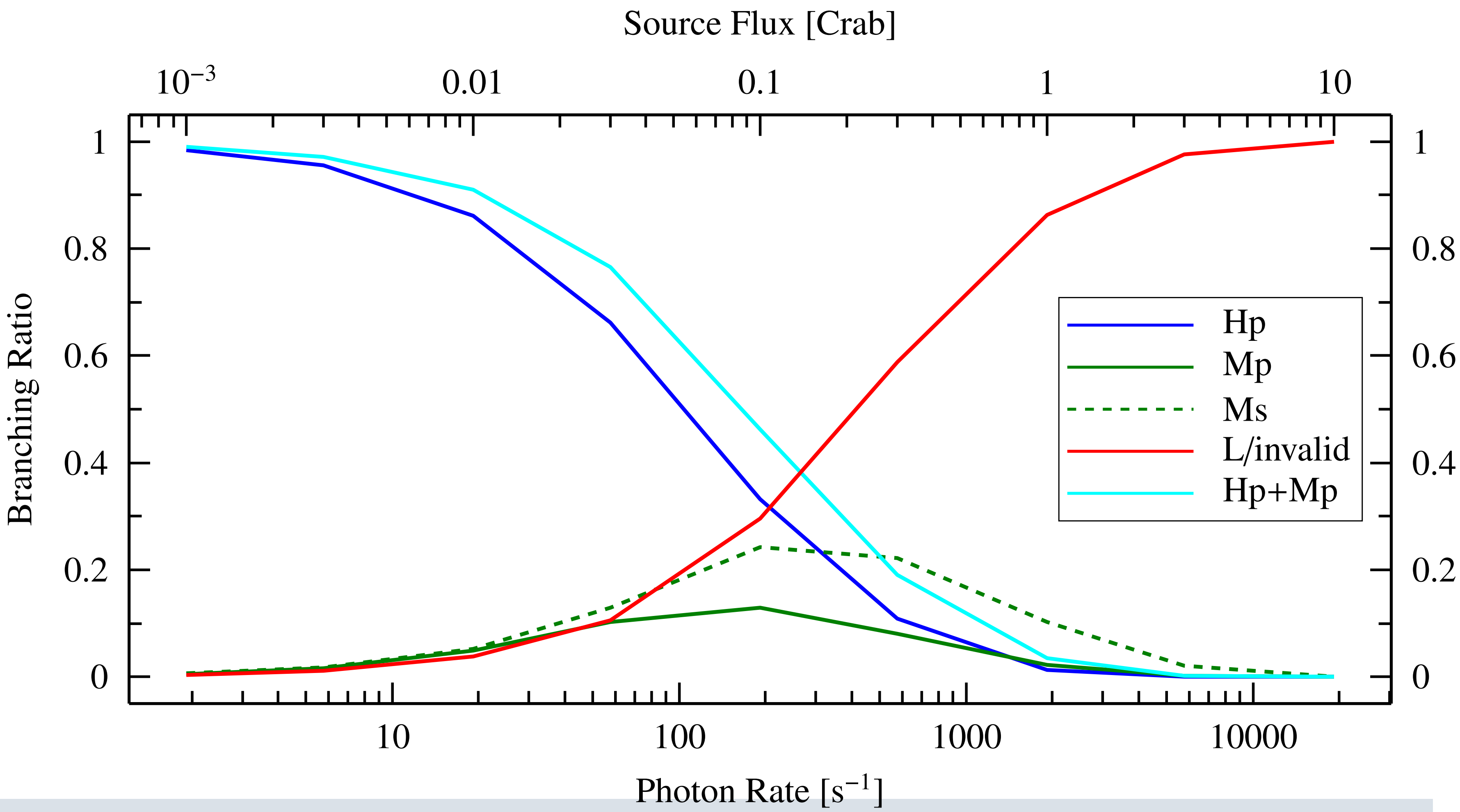
Dauser et al. (2019)

Microcalorimeter Effects – Grading

For microcalorimeters, SIXTE implements grading, i.e., varying energy resolution as a function of pulse separation. This is automatically included in every simulation.
Here, we supply a list of `post`- and `pre`-pulse distances and an RMF for every grade.

Example:
Reconstructed branching ratio plot for Resolve using SIXTE.

(Simulated Crab-like pointsource at different fluxes)

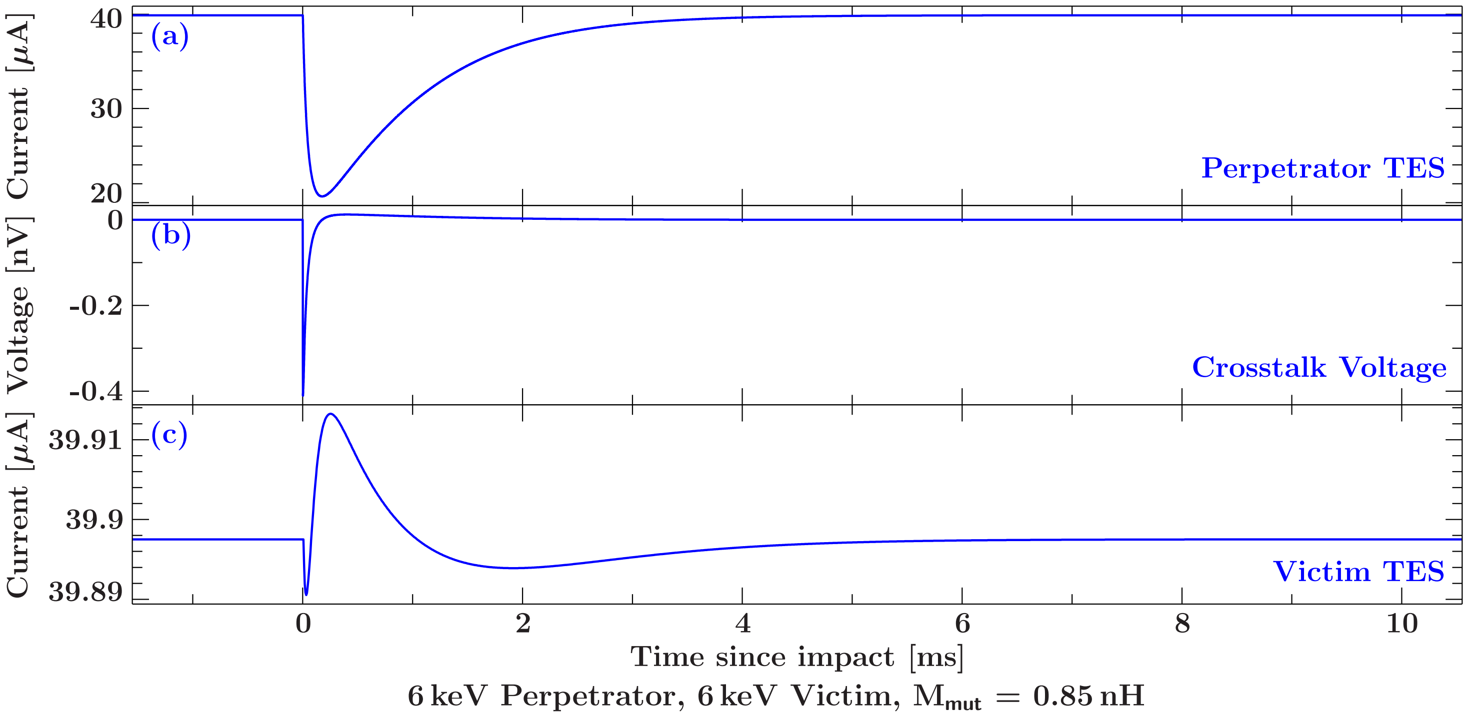


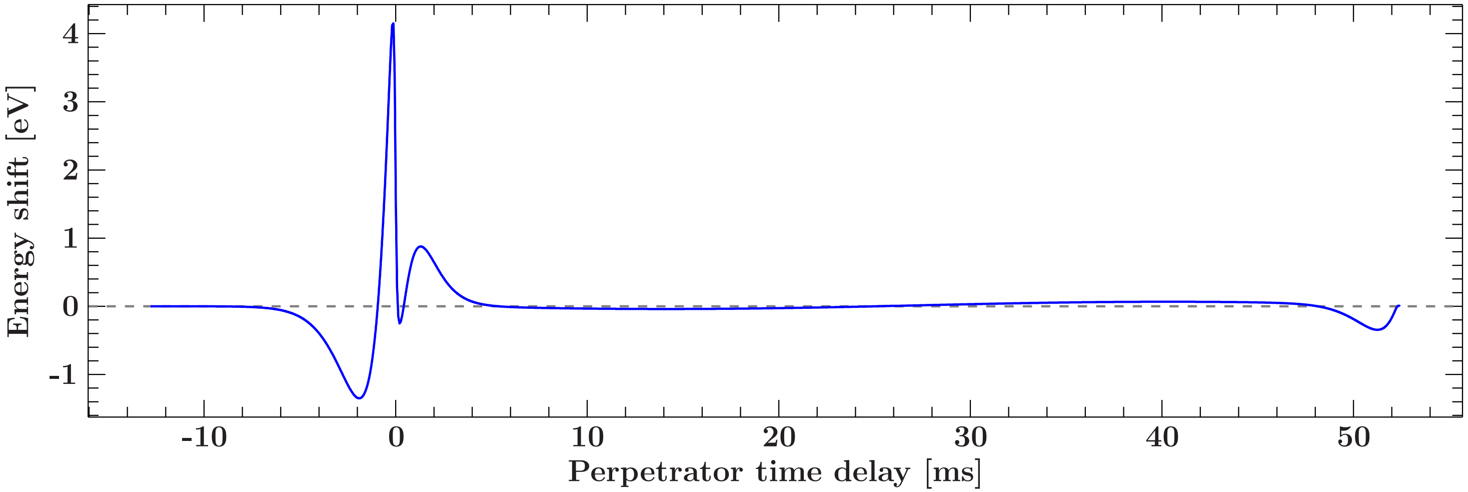
Microcalorimeter Effects – Crosstalk

Due to coupling between pixels (on focal plane or in readout), microcalorimeters can experience crosstalk.

This is significant for high count rate observations, with photons hitting coupled pixels during each other's "record" intervals.

Example: Electrical crosstalk in X-IFU via mutual inductance. Used `xifusim` simulations to characterize effect (top) and generate lookup table (energy shift vs. time, bottom).



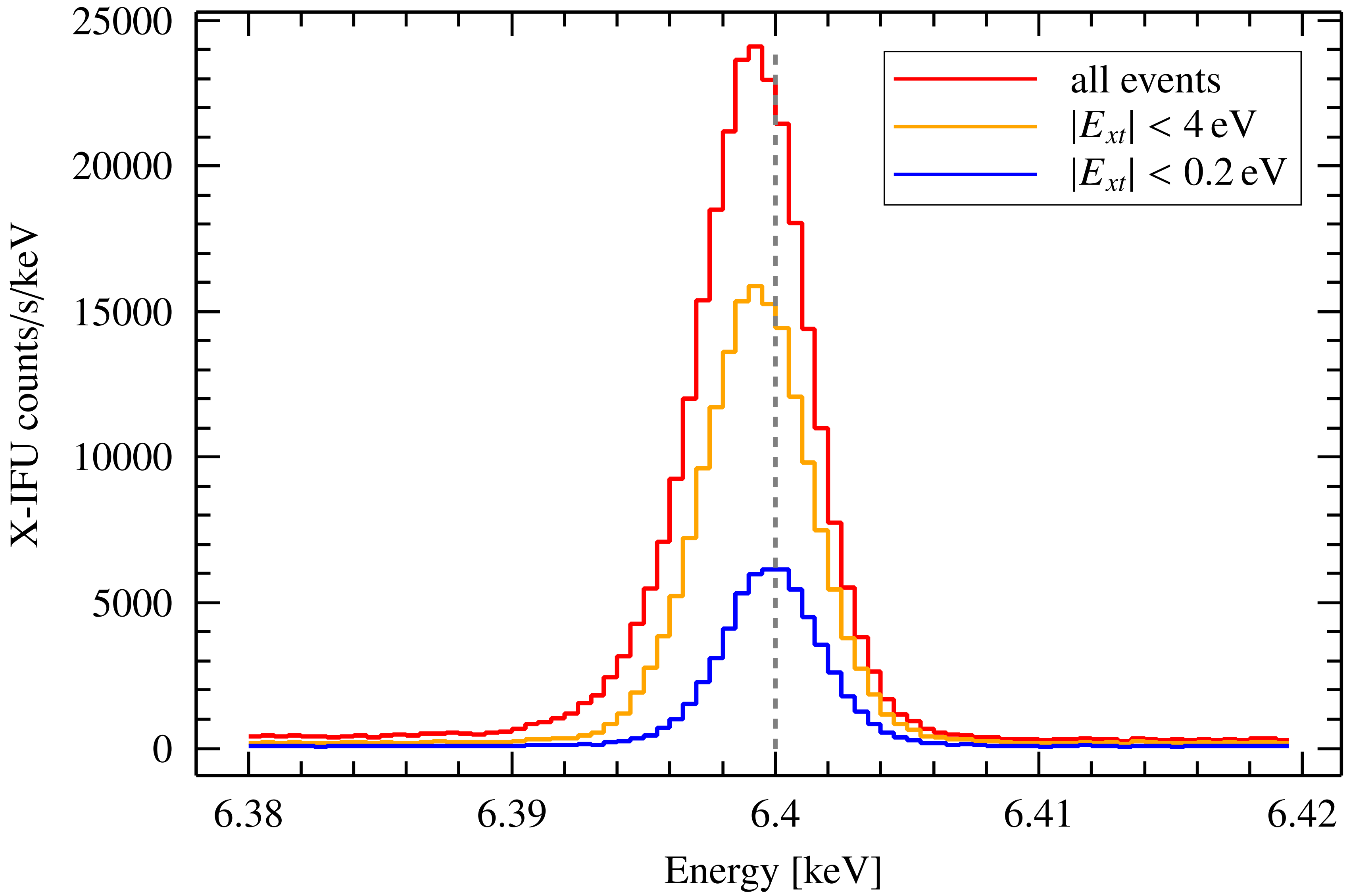


Microcalorimeter Effects – Crosstalk

SIXTE can use lookup tables to calculate crosstalk during simulations.

Right example: Gaussian emission line on top of Crab-like continuum. The line is shifted and distorted by crosstalk.

As crosstalk is predictable, users can filter out affected events. This restores the line shape, at a cost of throughput.



Running SIXTE

SIXTE Resources

First, check the SIXTE webpage:

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

- Documentation: 95p. manual and Dauser et al. (2019, A&A 630, 66)
- Help Desk: `sixte-support@lists.fau.de` – When in doubt, ask questions here
- Previous SIXTE workshops: videos, slides and tutorial materials
- Source Code: tarballs on webpage, or GitHub
- Useful SIMPUTS: Background AGN lists, ROSAT All-Sky Survey Catalogs and Soft X-ray Background, . . .

Installation: SIXTE can run locally on Linux and MacOS, and is also available on the JHU SciServer (via the `sixte_users` group). For either case, see

`https://www.sternwarte.uni-erlangen.de/sixte/installation/`

SIXTE Workflow

(1) Preparation of the simulation input

- Mostly use tool `simputfile`
- We also provide tools for more complex source geometries (`simputmultispec`) or merge multiple source catalogs (`simputmerge`)
- SIMPUT files are standard FITS files and can also be written, e.g., with scripts

(2) Running the simulation

- Use tool `sixtesim` and appropriate detector XML
- Output: one or multiple standard FITS event files

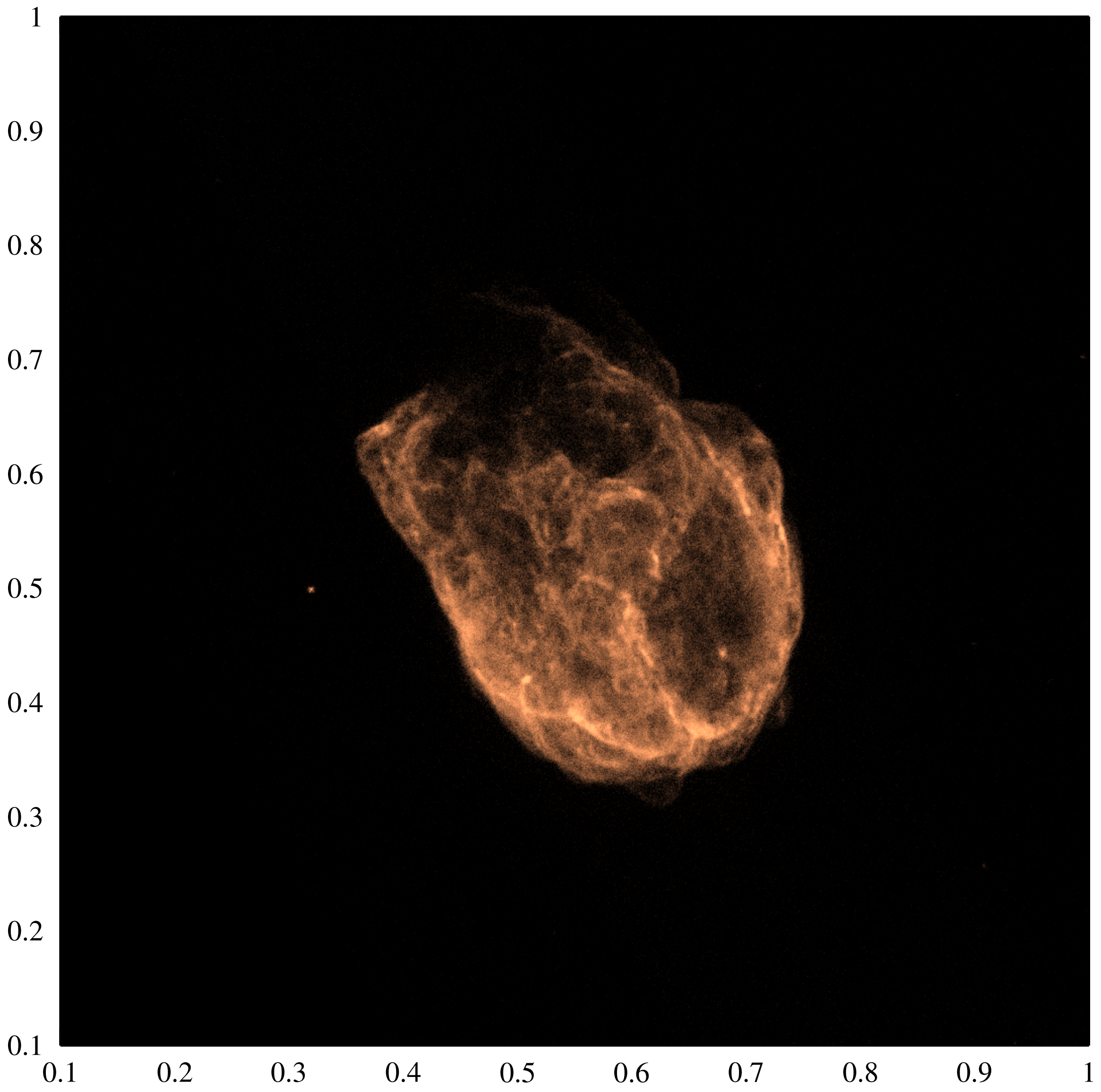
(3) Analyzing the simulation

- Tool `makespec`: Extract spectra
- Tool `imgev`: Create images
- Tool `makelc`: Create light curves
- SIXTE also has tools for exposure maps, ARF generation, ...
- Data products are compatible with common X-ray data analysis software

Example Simulations

N132D

```
#!/bin/sh
# create a simple powerlaw + vpshock model
# based on Xiao & Chen 2007

SrcRA=81.259404
SrcDec=-69.6437

# per paper: srcFlux=8.297e-11 erg/s/cm^2
# for the whole remnant,
# take this times 4, since their regions only
# cover  part of the remnant

$SIXTE/bin/simputfile           \
    Simput=n132d_flat.simput \
    Src_Name=n132d            \
    RA=${SrcRA} Dec=${SrcDec} \
    Emin=0.3 Emax=8           \
    srcFlux=32e-11         \
    Nbins=19900               \
    logEgrid=n              \
    Elow=0.1 Eup=15           \
    XSPECFile=plaw_shock.xcm    \
    ImageFile=n132d_0.75-7keV.fits \
    clobber=yes
```



N132D

```
#!/bin/bash

XRISM_INSTS=${SIXTE}/share/sixte/instruments/xrism

SrcRA=81.259404
SrcDec=-69.6437
# simulate microcalorimeter for Resolve
XMLDIR=$XRISM_INSTS/resolve

${SIXTE}/bin/sixtesim \
  XMLFile=$XMLDIR/resolve_baseline_GVclosed.xml \
  Simput=n132d_flat.simput \
  EvtFile=evt_resolve.fits \
  RA=$SrcRA Dec=$SrcDec \
  Exposure=300000 \
  background=no \
  prefix=output/

# radec2xy adds WCS coordinates to an event file
radec2xy EvtFile=output/evt_resolve.fits \
  RefRA=$SrcRA RefDec=$SrcDec Projection=SIN
```

N132D

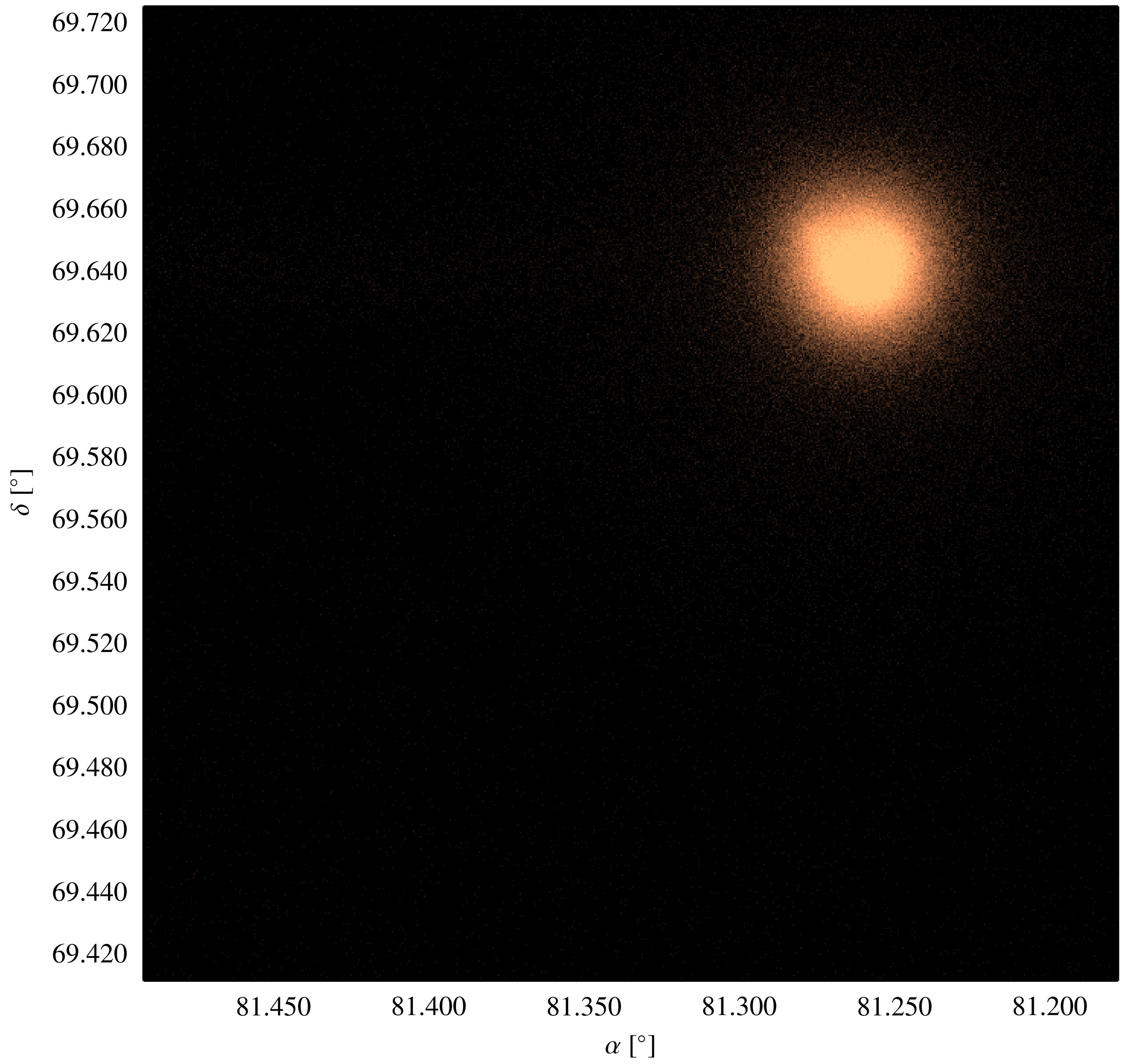
```
# simulate only a single chip for Xtend
# also use a shorter exposure, as Xtend has no Gate Valve
# this is still plenty of photons
# Note: the "/" at the end of the prefix argument is mandatory!
XMLDIR=$XRISM_INSTS/xtend

${SIXTE}/bin/sixtesim \
  XMLFile=$XMLDIR/xtend_ccd2.xml \
  Simput=n132d_flat.simput \
  EvtFile=evt_xtend.fits \
  RA=$SrcRA Dec=$SrcDec \
  Exposure=10000 \
  prefix=output/

radec2xy EvtFile=output/chip2_evt_xtend.fits \
  RefRA=$SrcRA RefDec=$SrcDec Projection=SIN
```

N132D

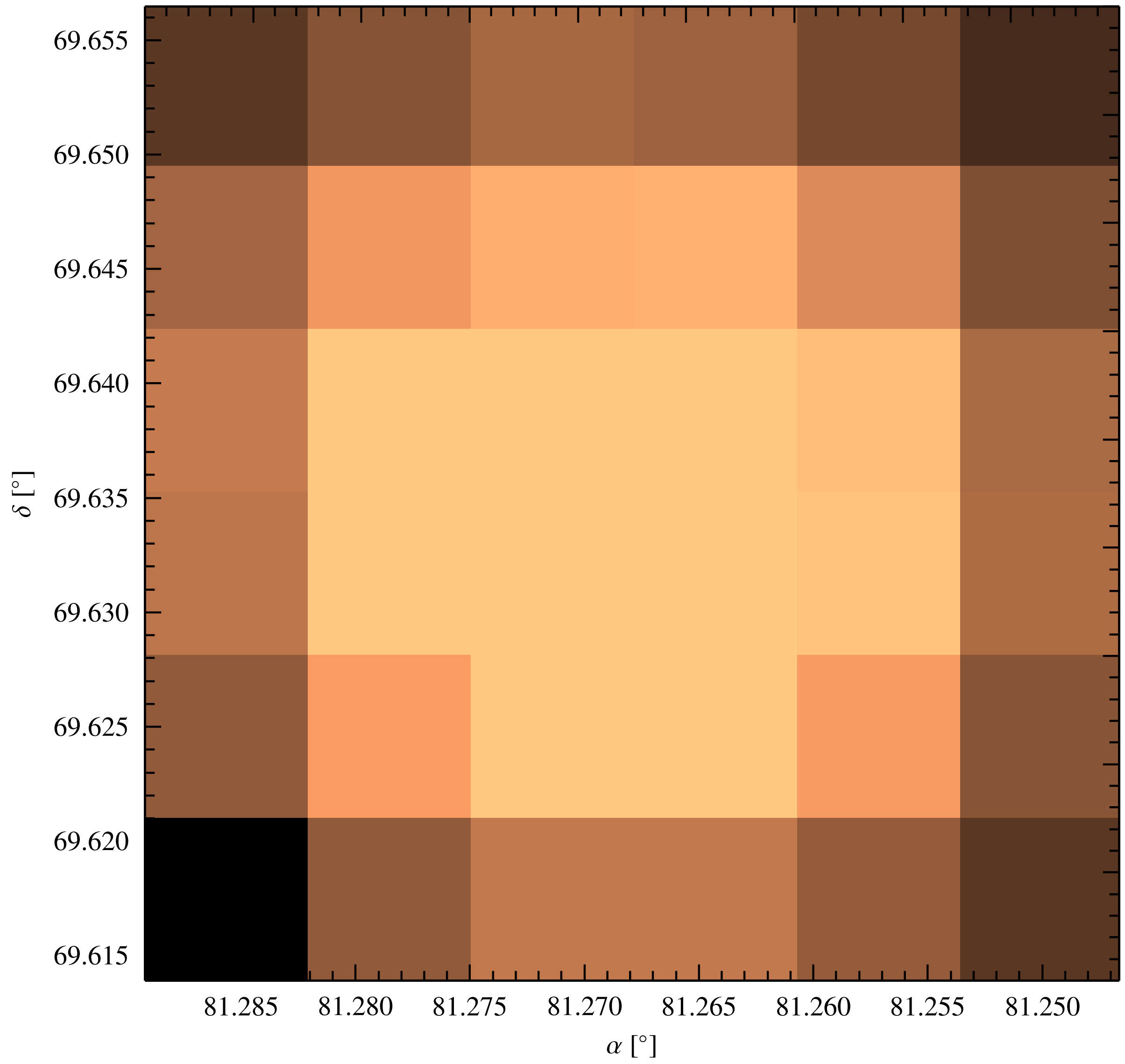
```
#!/bin/bash

# create an image of the source per detector
# here, we use the same tool (imgev) with different parameters
SrcRA=81.259404
SrcDec=-69.6437

# Since this source is no longer at (0,0), we need to adjust
# CRVAL in imgev

# Resolve
$SIXTE/bin/imgev                                    \
    EvtFile=output/evt_resolve.fits                 \
    Image=output/img_resolve.fits                   \
    CoordinateSystem=0 Projection=TAN               \
    NAXIS1=6 NAXIS2=6                               \
    CUNIT1=deg CUNIT2=deg                           \
    CRVAL1=$SrcRA CRVAL2=$SrcDec \
    CRPIX1=3.5 CRPIX2=3.5                           \
    CDELT1=-85.12516e-04 CDELT2=85.12516e-04        \
    history=true clobber=yes
```

N132D

```
# Xtend
$SIXTE/bin/imgev                                      \
    EvtFile=output/chip2_evt_xtend.fits               \
    Image=output/img_xtend.fits                       \
    CoordinateSystem=0 Projection=TAN                 \
    NAXIS1=640 NAXIS2=640                             \
    CUNIT1=deg CUNIT2=deg                             \
    CRVAL1=$SrcRA CRVAL2=$SrcDec \
    CRPIX1=473.34 CRPIX2=473.34                       \
    CDELT1=-4.9110668e-04 CDELT2=4.9110668e-04        \
    history=true clobber=yes
```



69.720
69.700
69.680
69.660
69.640
69.620
69.600
69.580
69.560
69.540
69.520
69.500
69.480
69.460
69.440
69.420
δ [°]
81.450
81.400
81.350
81.300
81.250
81.200
α [°]

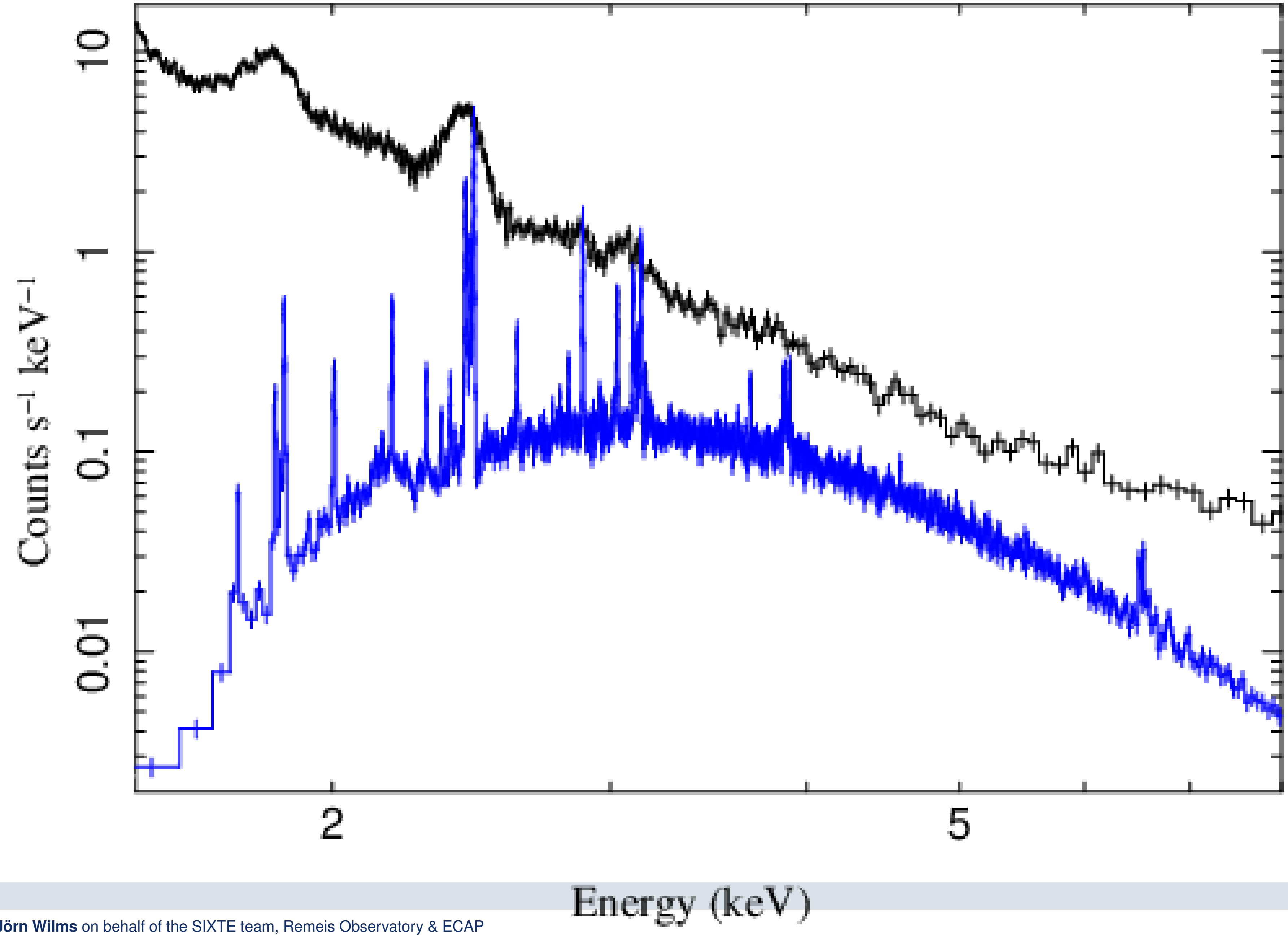


69.655
69.650
69.645
69.640
69.635
69.630
69.625
69.620
69.615
δ [°]
81.285
81.280
81.275
81.270
81.265
81.260
81.255
81.250
α [°]

N132D

```bash
#!/bin/bash

# Same as before
XRISM_INSTS=${SIXTE}/share/sixte/instruments/xrism

# Resolve
XMLDIR=$XRISM_INSTS/resolve

$SIXTE/bin/makespec                              \
     EvtFile=output/evt_resolve.fits             \
     Spectrum=output/spec_resolve.pha            \
     RSPPath=${XMLDIR}                           \
     clobber=yes

# Xtend
XMLDIR=$XRISM_INSTS/xtend

$SIXTE/bin/makespec                              \
    EvtFile=output/chip2_evt_xtend.fits          \
    Spectrum=output/chip2_spec_xtend.pha         \
    RSPPath=${XMLDIR}                            \
    clobber=yes \
    usepha=yes
```

N132D – spectra

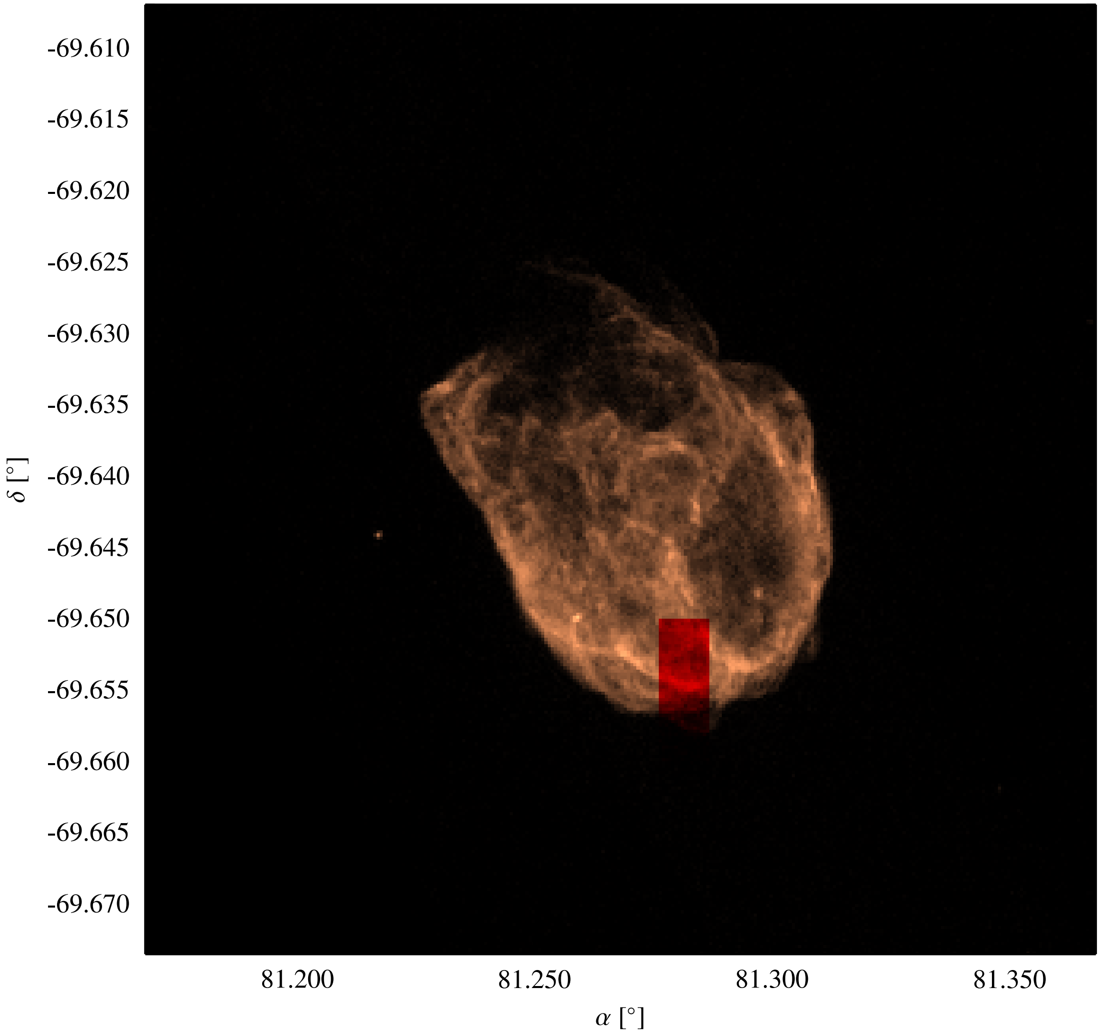


N132D – analytics

SIXTE tracks origin of events

(photons and sources have ID)

Consider red region in N132D

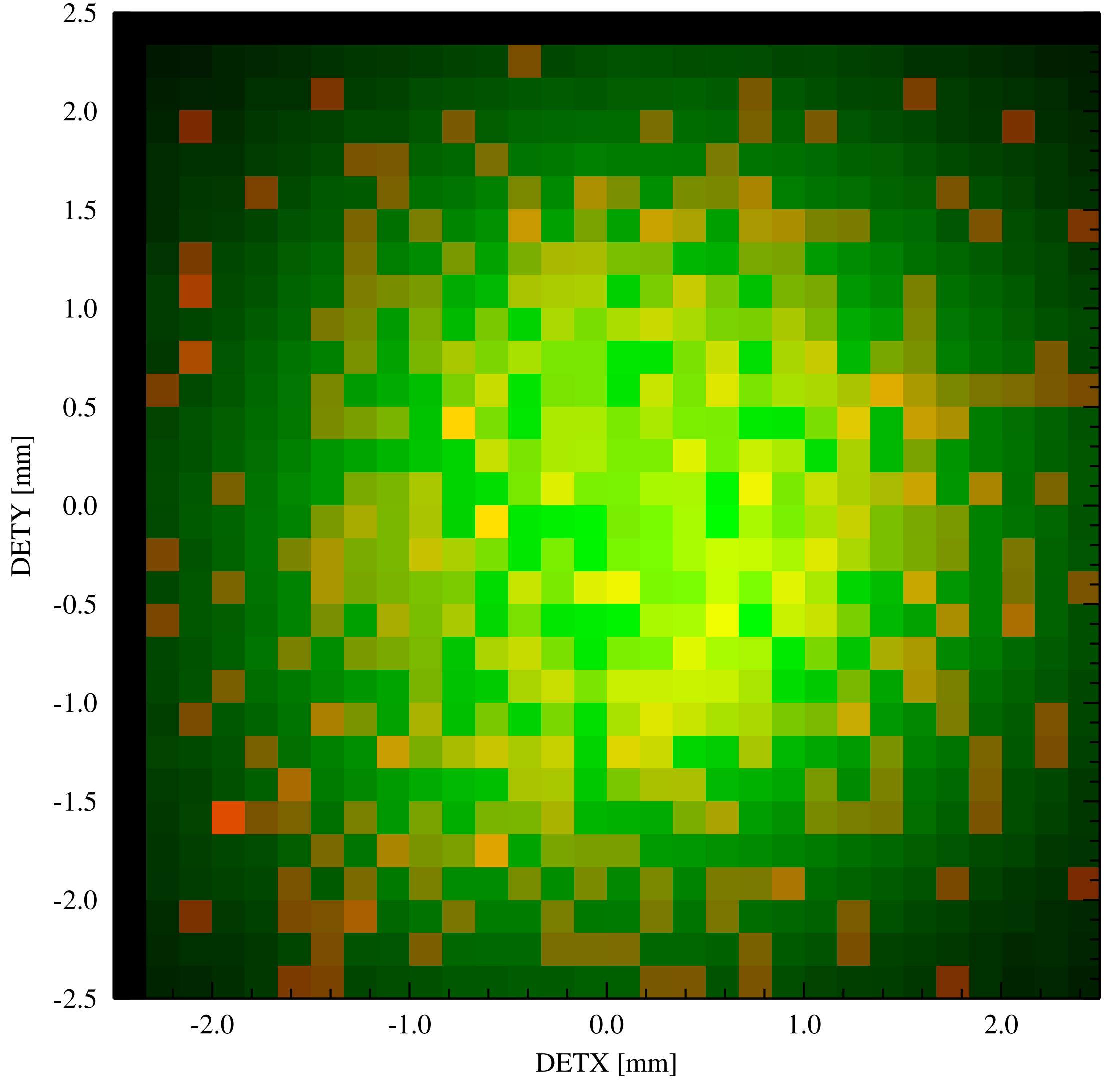


N132D – analytics

SIXTE tracks origin of events

(photons and sources have ID)

Impact of photons from “red region” in detector plane

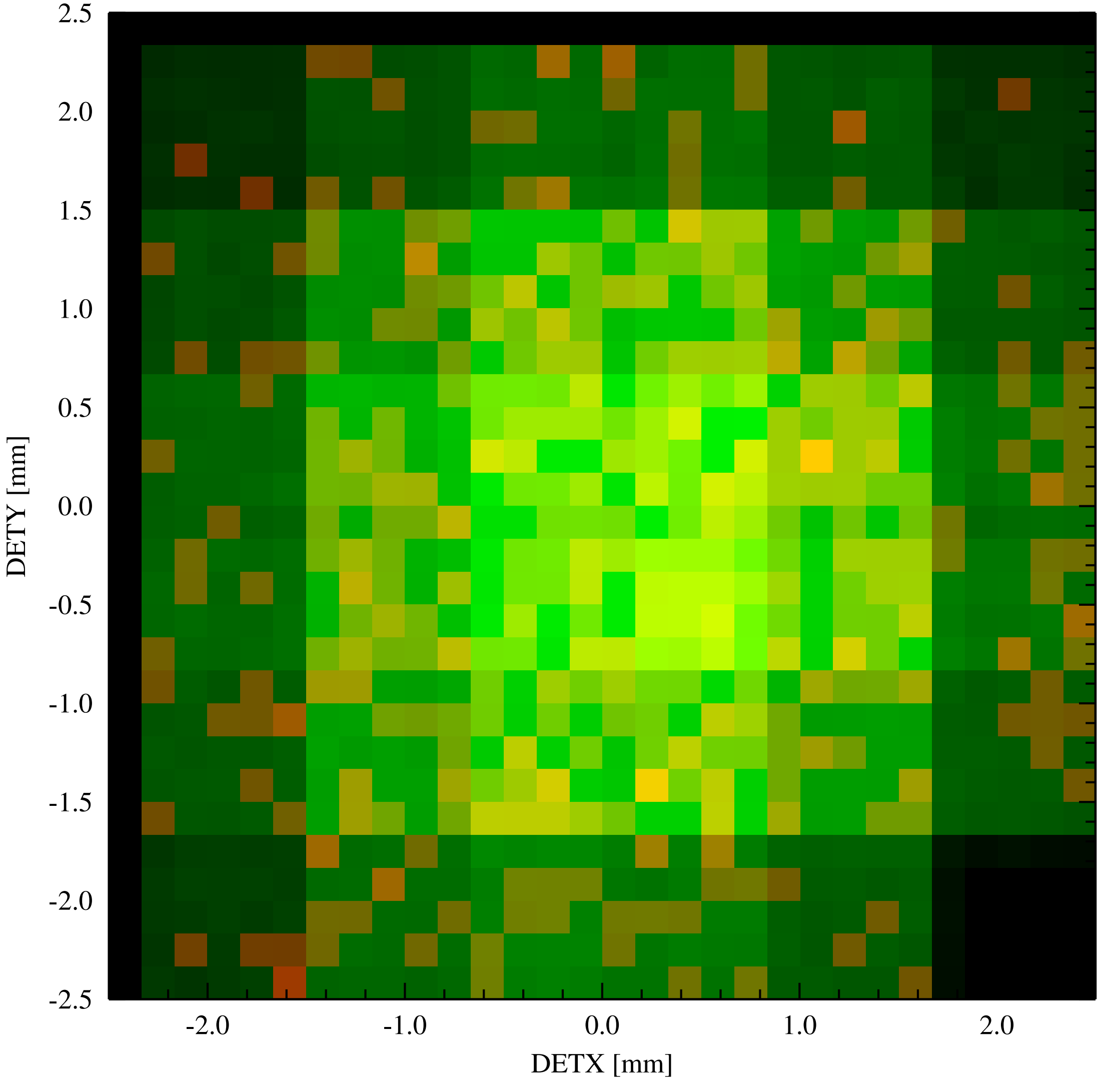


N132D – analytics

SIXTE tracks origin of events

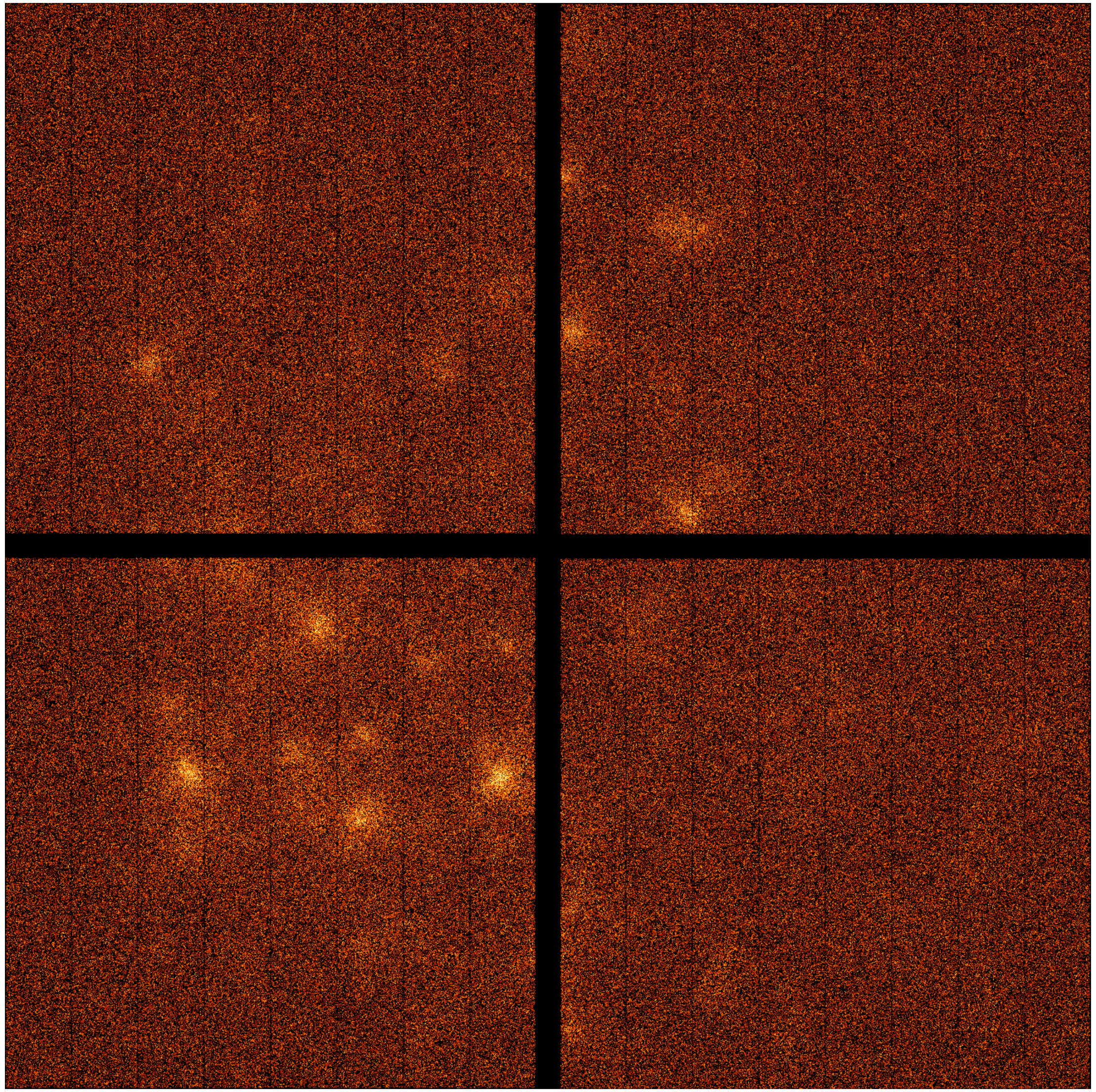
(photons and sources have ID)

Pixel assignment of photons from “red region”



Simulation Example – Survey

Simulate the Chandra Deep Field South with Xtend:



Overall 762 point sources and 50 clusters, with one spectrum per source type.

A 1 Ms simulation took ∼5 minutes to run.

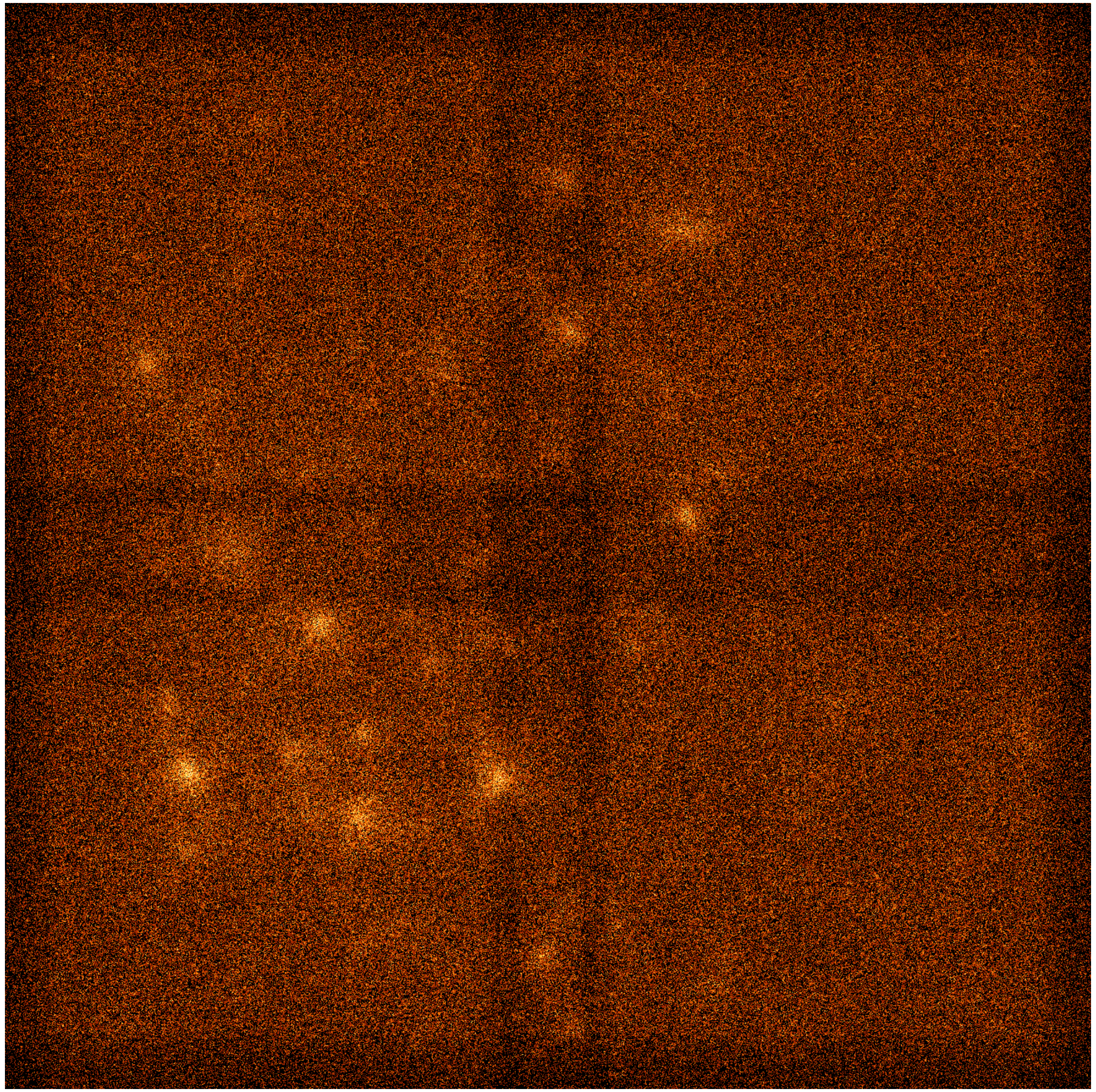
Simulation Example – Survey

Simulate the Chandra Deep Field South with Xtend:

Overall 762 point sources and 50 clusters, with one spectrum per source type.

A 1 Ms simulation took ∼5 minutes to run.

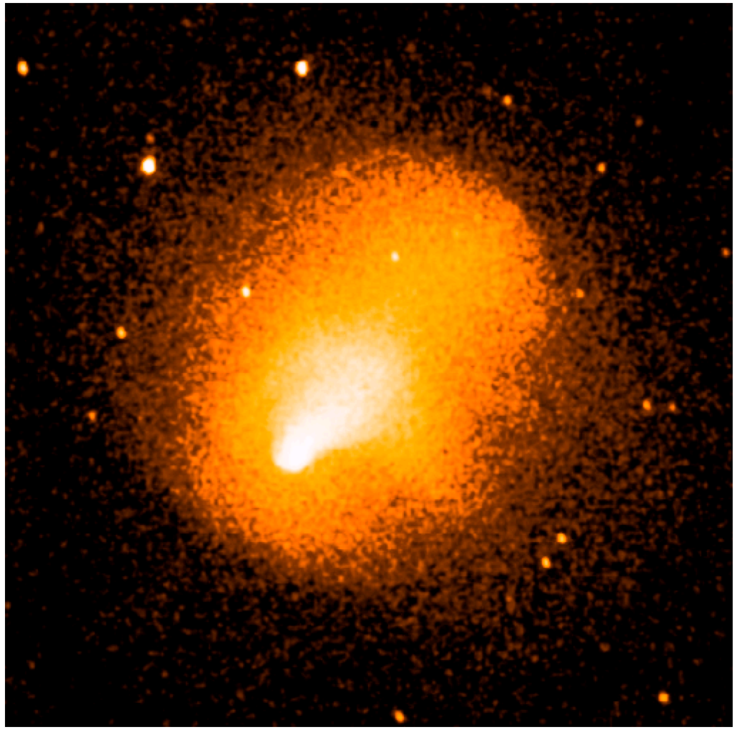
SIXTE also supports attitude files. Fix chip gaps by dithering.

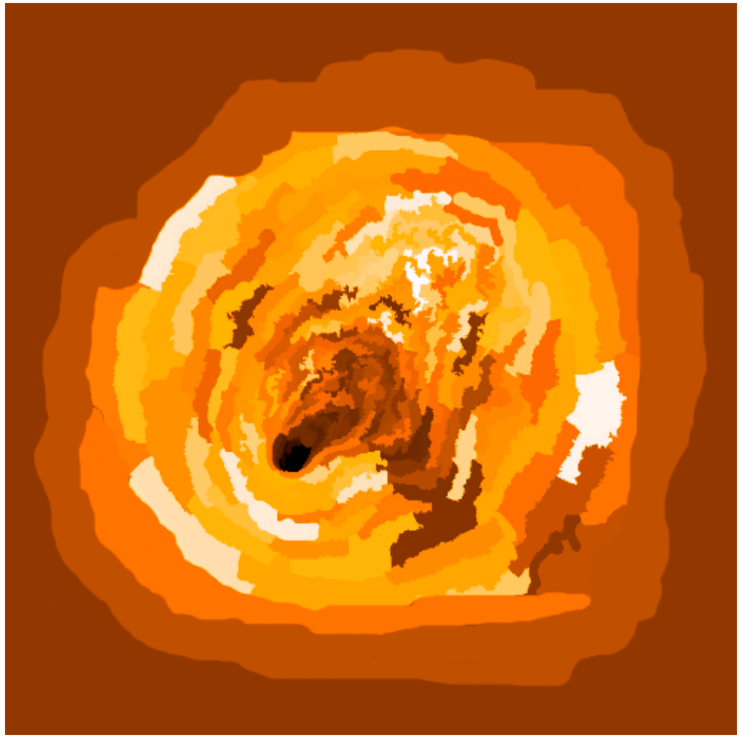


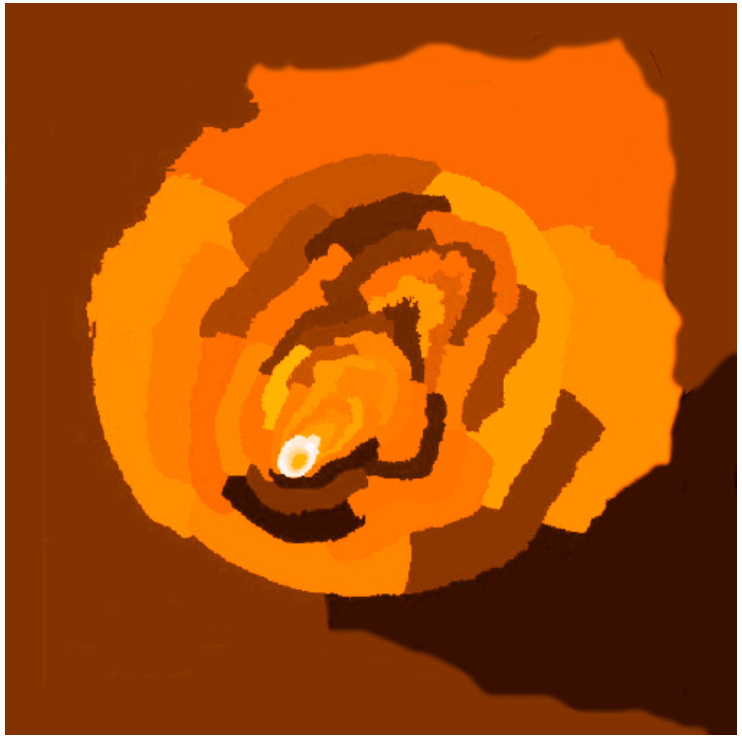
Simulation Example – Galaxy Cluster

For extended sources, SIXTE provides the tool `simputmultispec`, which takes flux and parameter maps to build a spatially variable source.

Example: Luminosity and parameter (temperature, abundances) maps of Abell 2146 obtained by Russel et al. (2012) with *Chandra*

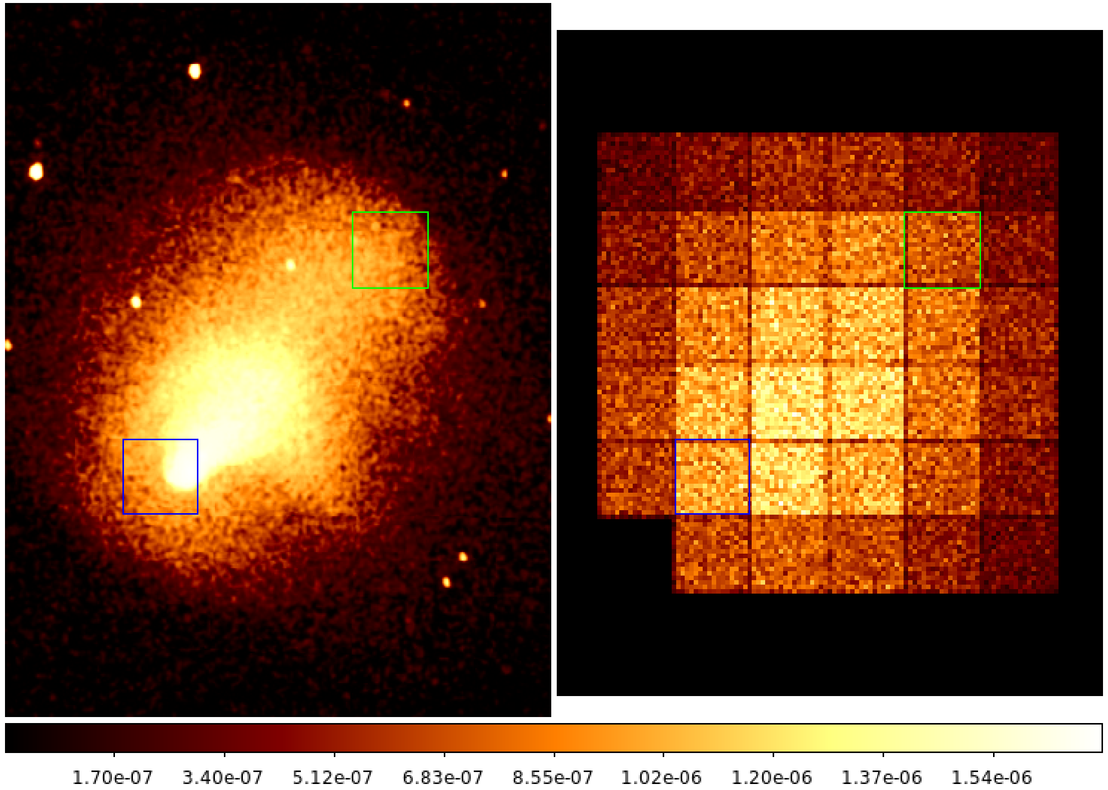


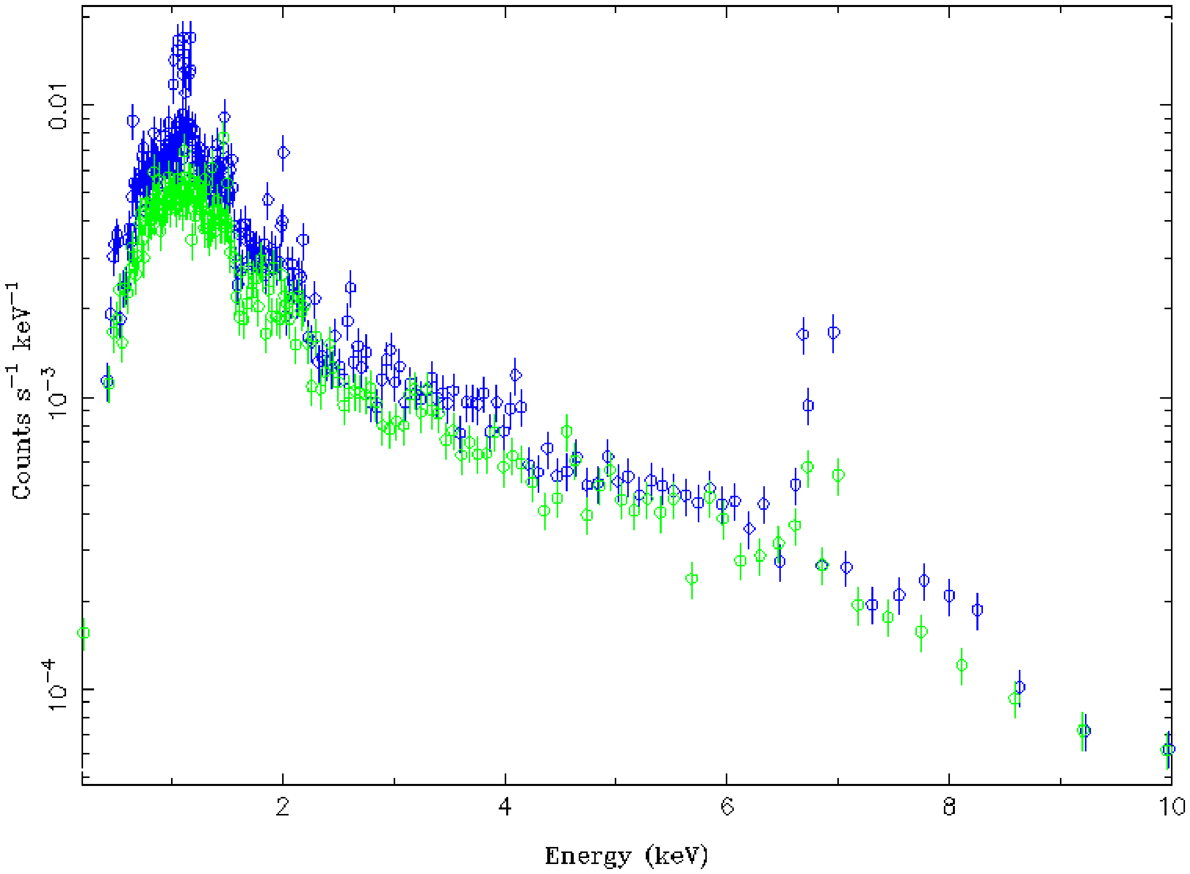




Simulation Example – Galaxy Cluster

Simulate 1 Ms with Resolve for this source (runtime: 70 seconds).
We can then extract single pixel spectra and compare them:





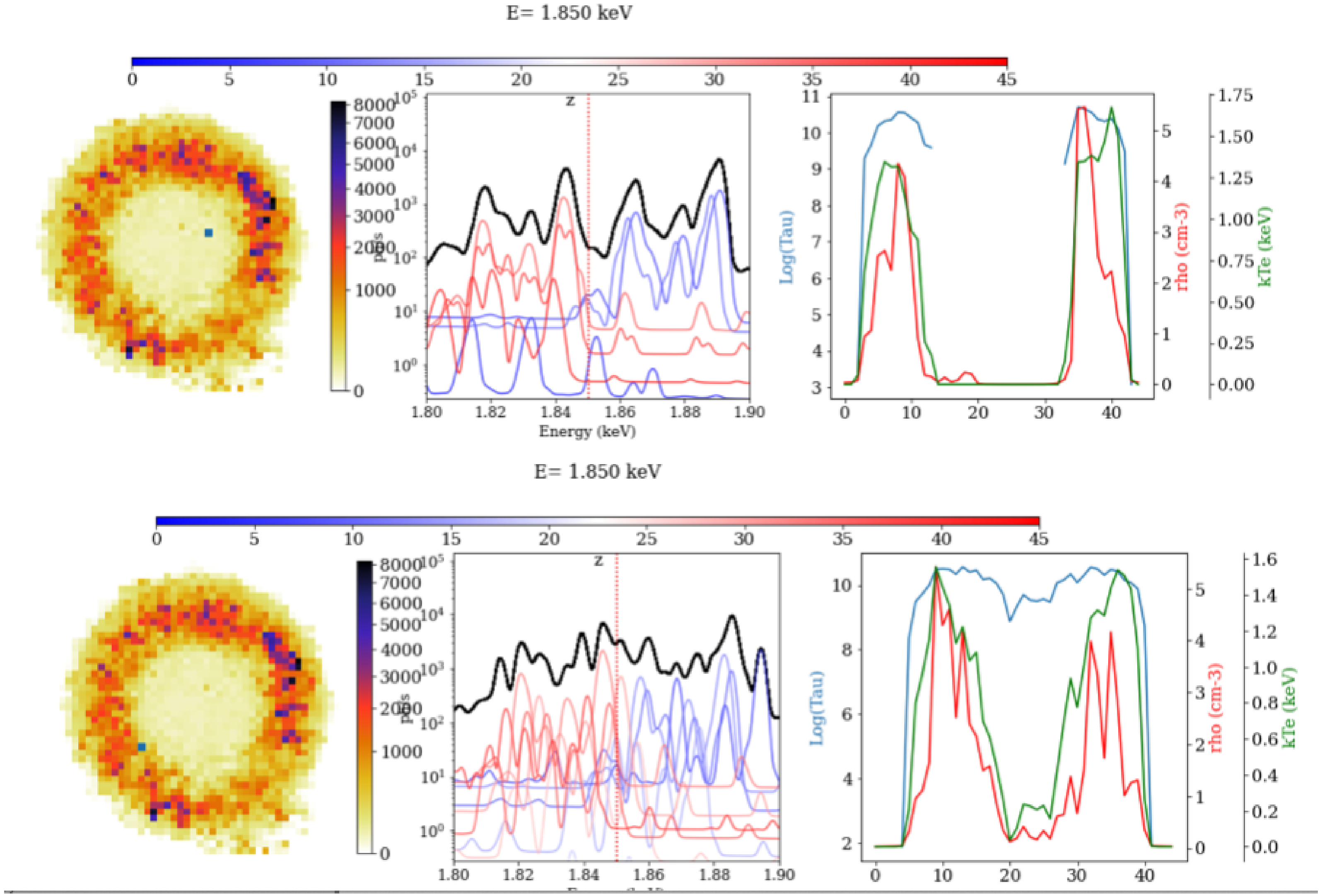
Simulation Example – Cas A

Extreme example: Use 3D simulations of extended sources (with help from Fabio Acero, CEA)

Here: Use Cas A simulation of Orlando et al. (2016) as input.

Subdivide into 191^3 voxels (depth included) and generate spectra, then sum up spectra along line of sight
$\Longrightarrow$ 23381 individual spectra, 4.4 GB

Parameters vary strongly along line of sight, including redshift!

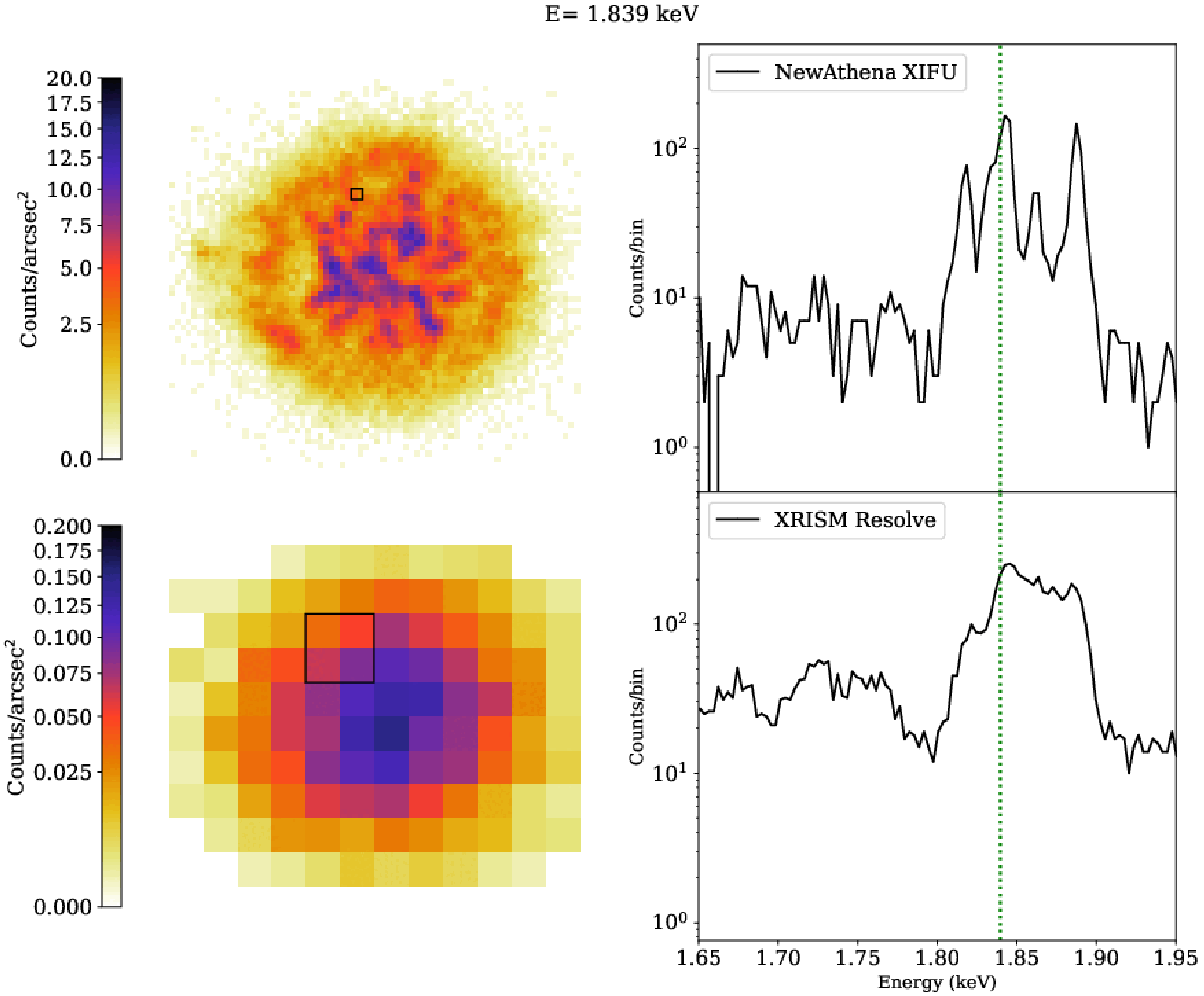


Simulation Example – Cas A

Extreme example: Use 3D simulations of extended sources (with help from Fabio Acero, CEA)

After simulation, make subimages scanning over Si-Line

$\Longrightarrow$ 3D tomography



Conclusions

When to use SIXTE

When not to use SIXTE

but `fakeit` or similar tools

- fainter point sources ($\lesssim$1 mCrab)
  $F_{0.5-2\,\mathrm{keV}} \lesssim 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$,
  $F_{2-10\,\mathrm{keV}} \lesssim 2 \cdot 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$,
  unless background starts to become important
- quick estimates

When to use SIXTE

and *not* `fakeit`

- bright sources ($\gtrsim$ 10 mCrab)
  i.e., many "famous" AGN, galactic sources,
  where high-count rate effects become relevant
- faint sources, if background or exposure map matters
- imaging simulations
  e.g., galaxy clusters, Supernova remnants
  - point source detection sensitivity
  - point sources in crowded fields
  - extended sources
- variability
  e.g., reverberation mapping, pulses, QPOs, ...

When in doubt, you can also ask the SIXTE helpdesk

How to run SIXTE

Installation: SIXTE can run locally on Linux and MacOS, and is also available on the JHU SciServer (via the `sixte_users` group). For either case, see

`https://www.sternwarte.uni-erlangen.de/sixte/installation/`

Examples:

`https://www.sternwarte.uni-erlangen.de/~sixte/downloads/xrism_workshop/sixte_tutorial.pdf`

1. Getting started: point sources with Resolve and Xtend
2. Bright source simulations
3. Simulating the first light observation

Note: We use versions of the Cycle 1 instrument files, w/gate valve closed. We will update these on the SIXTE webpages once better PSFs and other instrument descriptions become available.

Your job now: talk with your neighbors: What would *YOU* want to simulate?

Examples

1. extended sources: SNR, clusters,. . .
2. XRB/AGN accretion disk winds
3. HMXBs: X-ray wind signatures, binary signatures
4. AGNs: spectral signatures, winds

Discuss about how you would setup a realistic simulation!

Think about: objects? variability? spectroscopy? foregrounds? measurables?