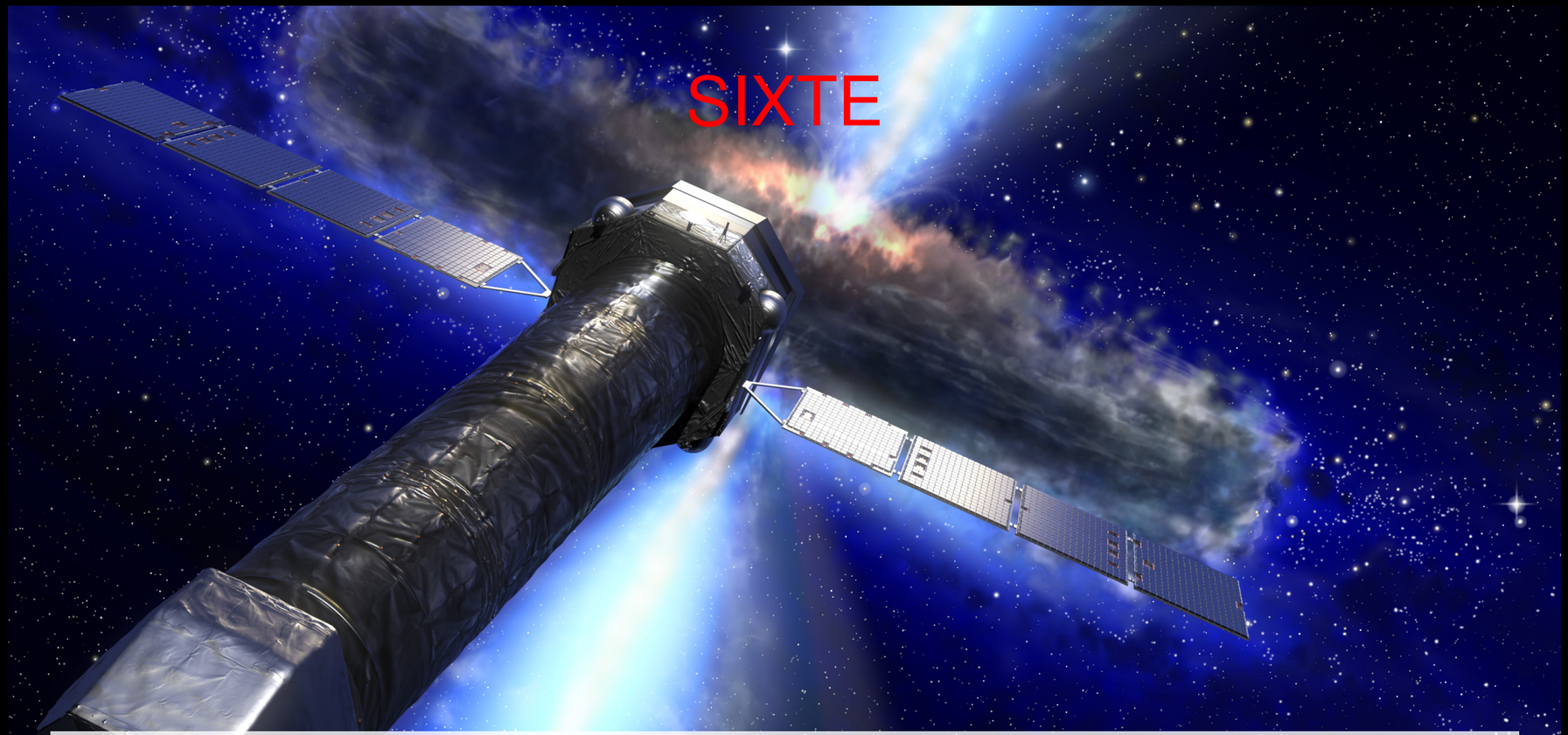
SIXTE



Jörn Wilms (he/him) on behalf of the SIXTE team:
Lea Dauner, T. Dauser, Esin Gulbahar, C. Kirsch, M. Lorenz, K. Pal,
N. Reinmann P. Thalhammer, J. Stierhof (ECAP), E. Cucchetti, P. Peille (CNES),
Maite Ceballos, Bea Cobo (IFCA), Jessica Planelles (Alicante) and many others

ERLANGEN CENTRE
FOR ASTROPARTICLE
PHYSICS

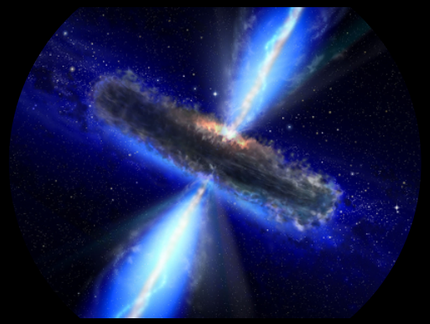
ASTROSAT

XMM

IXPE

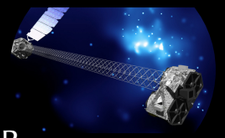
SRG

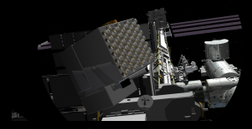
HXMT



Chandra

NuSTAR





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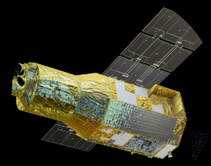
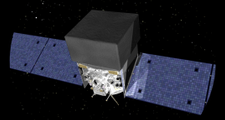




XRISM

Fermi

Einstein Probe

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

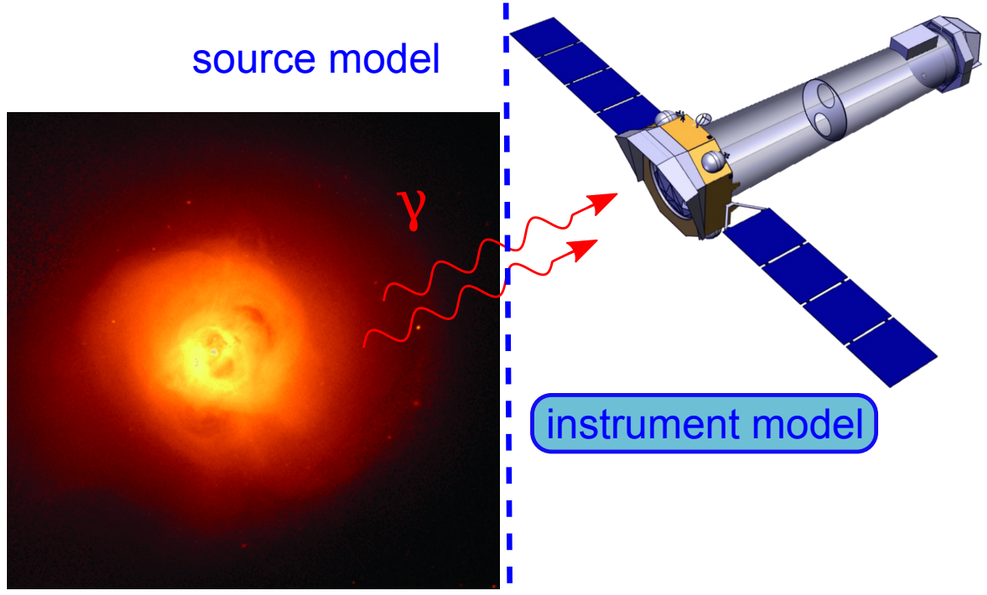
Instrumentalists:

- 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.

SIXTE Overview



SImulation of X-ray TElescopes

SIXTE simulates the full detection chain from the astrophysical source through imaging and detection.

NewAthena, eROSITA, XMM, Suzaku, XRISM, THESEUS, AXIS [+HEX-P, ARCUS, LOFT, IXO, GRAVITAS,. . .]

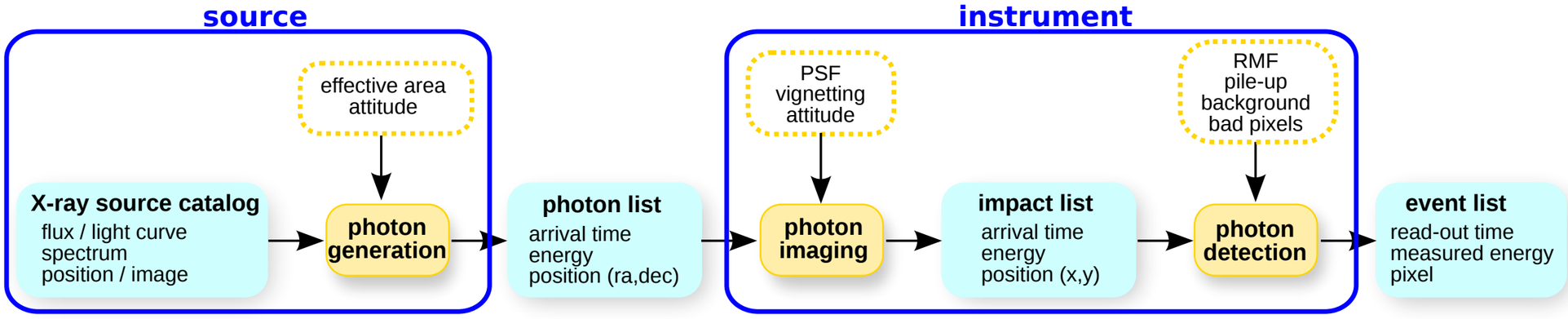
Simulation output: standard FITS files

looks like a real observation

Analysis tools for image creation, spectral extraction, exposure maps, and ARF generation are provided as part of SIXTE

output then analyzable w/your favorite analysis tools

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



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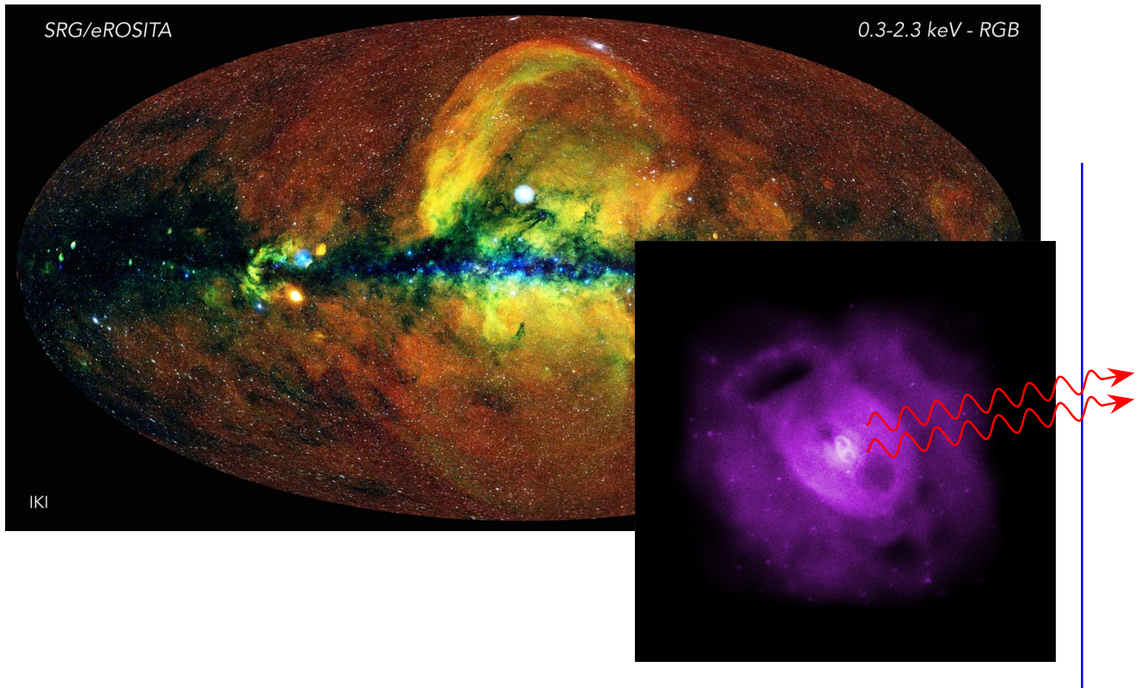

Source model: properties of the sources: Positions, Extended source/point source, spectral shape, variability, polarization. . .

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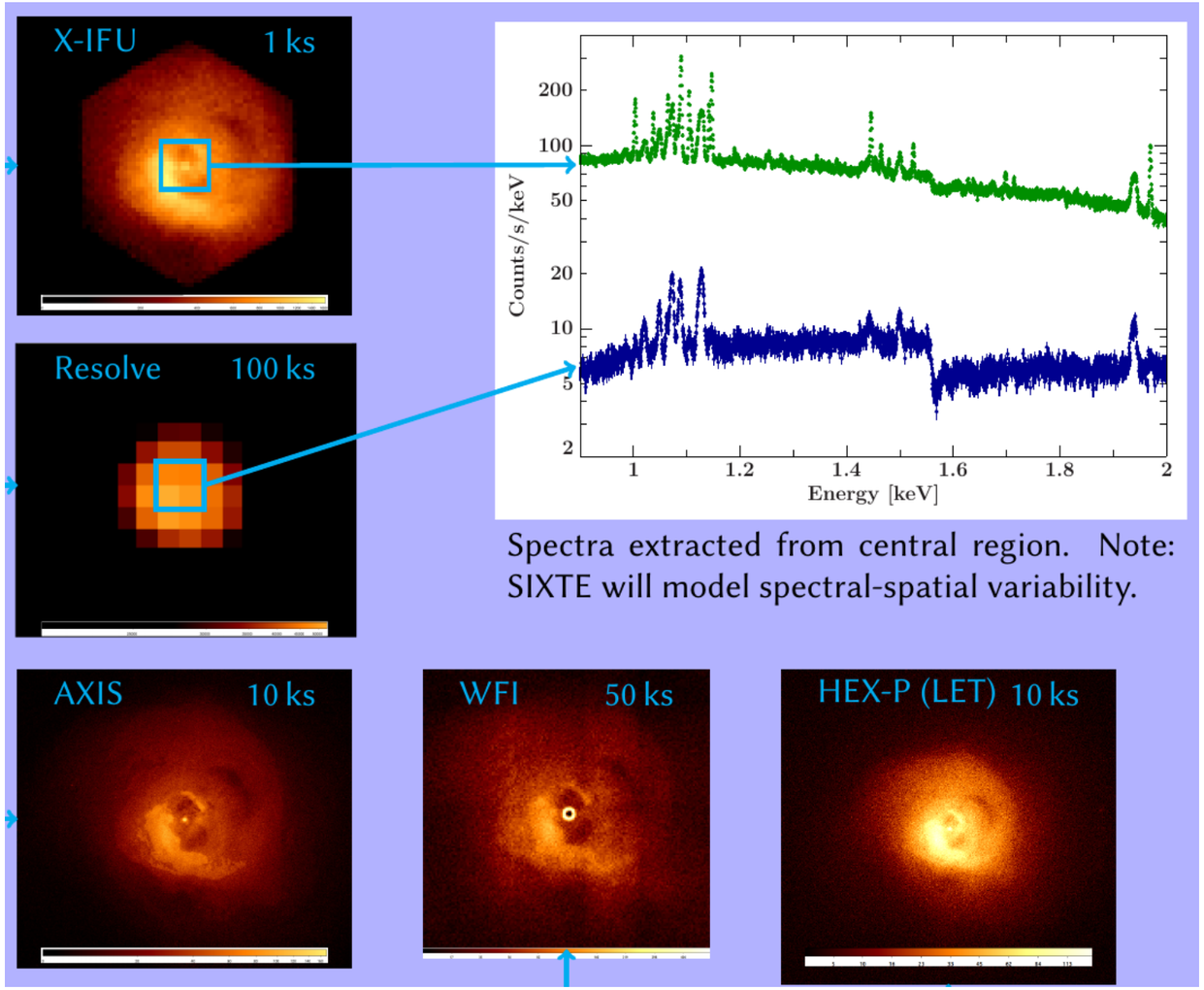


Spectra extracted from central region. Note: SIXTE will model spectral-spatial variability.

Per Cluster

Setup of good simulation input is *hard*

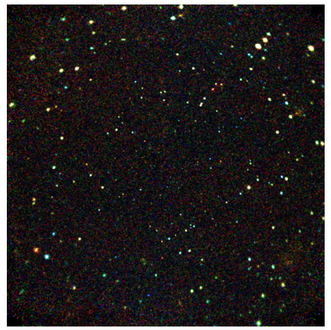
$\Longrightarrow$ Input should be instrument independent and reusable

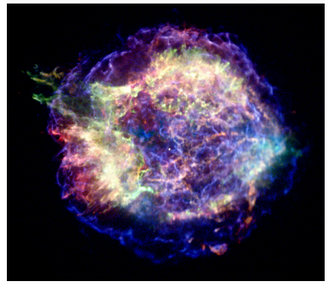
Solution: SIMPUT

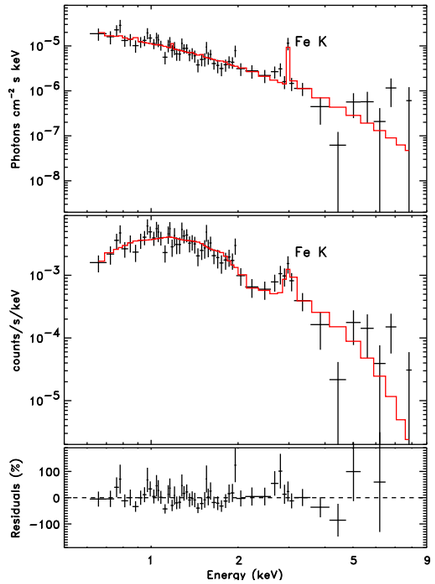
$\Longrightarrow$ instrument independent, used by multiple simulators

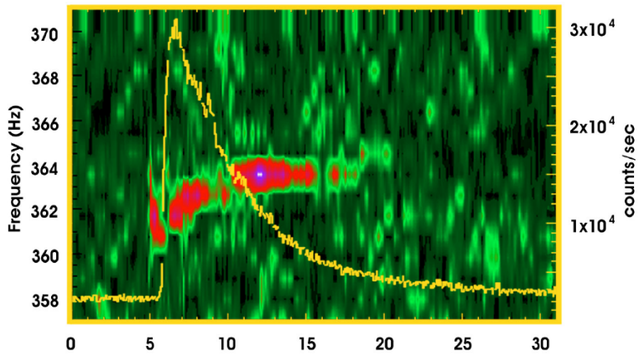
currently supported by `SIXTE`, `simx`, `SOXS`, and `MARX`; general s/w at Remeis SIXTE URL, also `pyXSIM`

Source Model: SIMPUT









sources are characterized by:

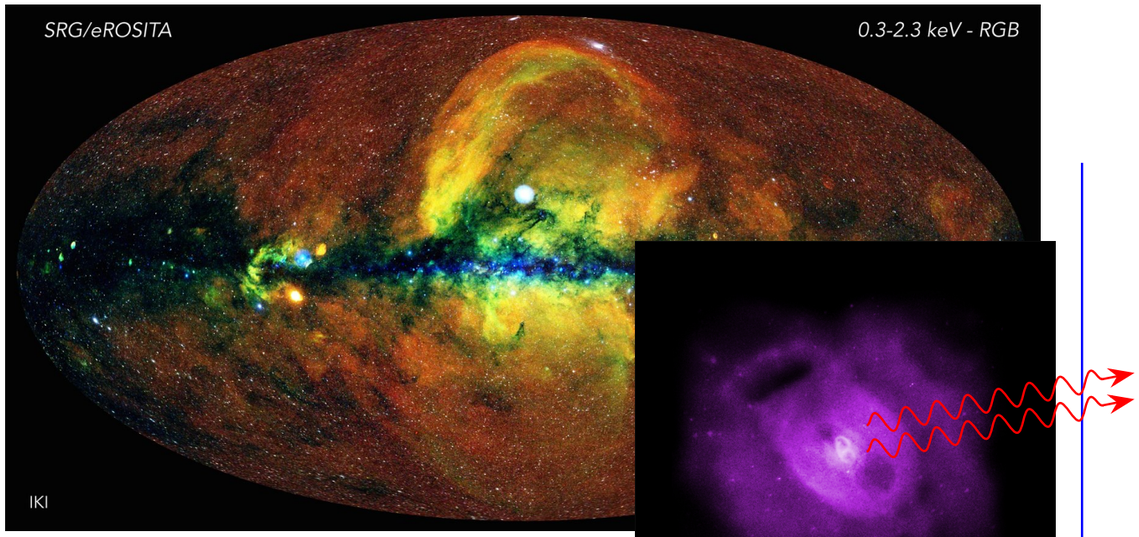
- source properties:
  - spectral shape
  - positions
  - light curves, pulse profiles, power spectra. . .
  - spatial extent
  - photon lists from MHD simulations
  - “data cubes” (e.g., cosmology)
- format allows reuse of common properties of sources

  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`

Instrument Model



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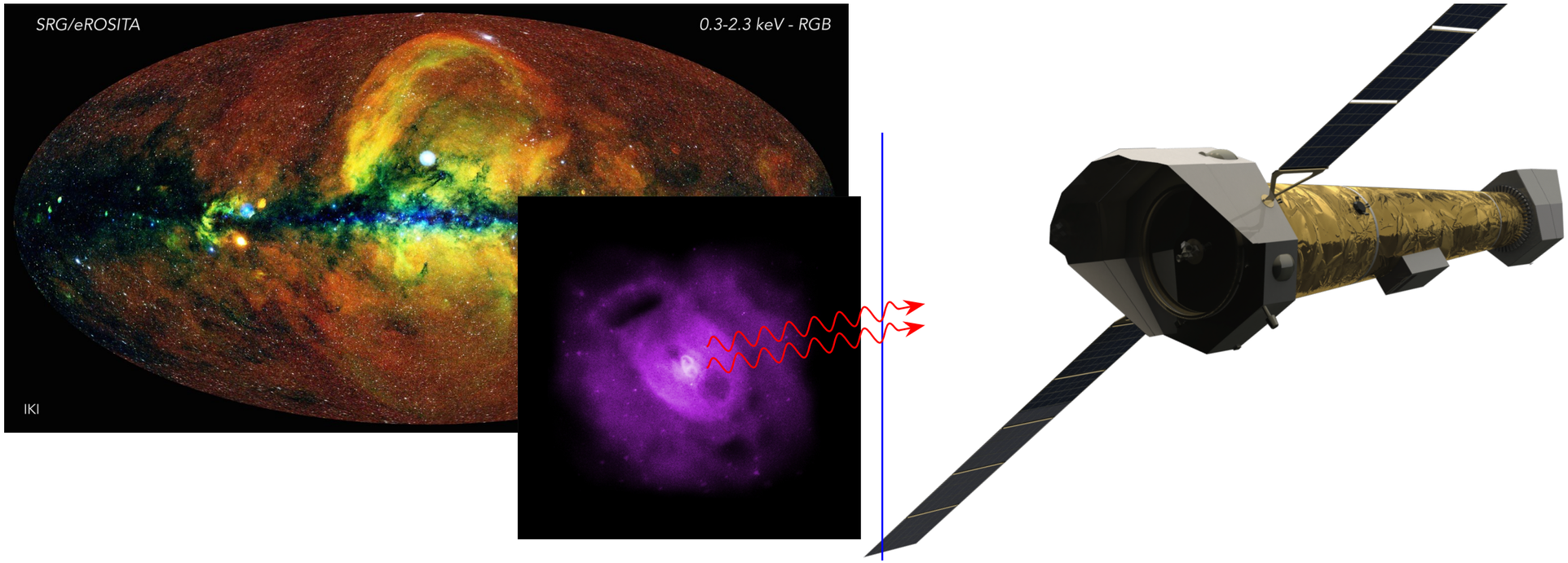


Source model: properties of the sources: Positions, Extended source/point source, spectral shape, variability, polarization. . .

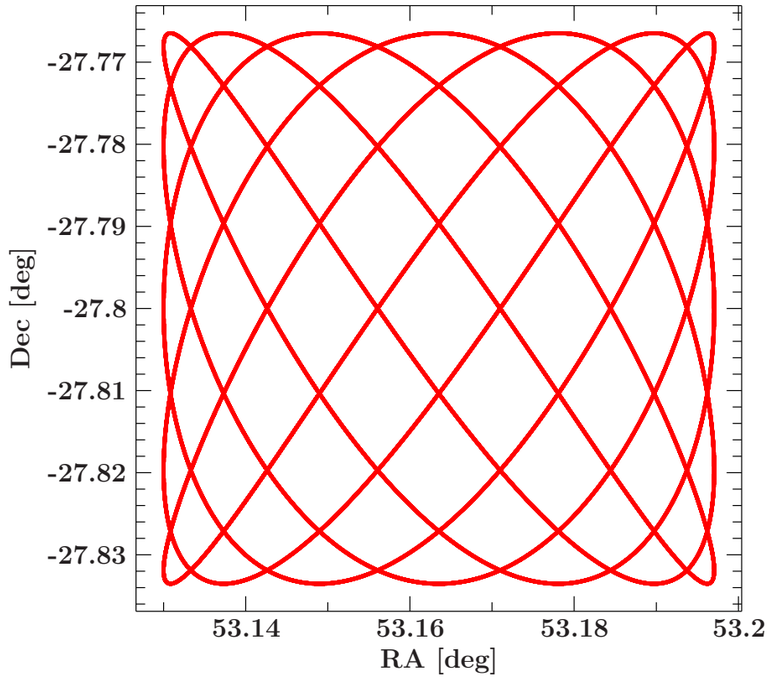
Instrument model: properties of the instrument: Imaging parameters, detection process, data processing chain (on board and on ground)

Instrument Model

Typical aspects handled by satellite and instrument model in SIXTE:

- Pointing strategy

  staring, dithering, mosaicing,. . .



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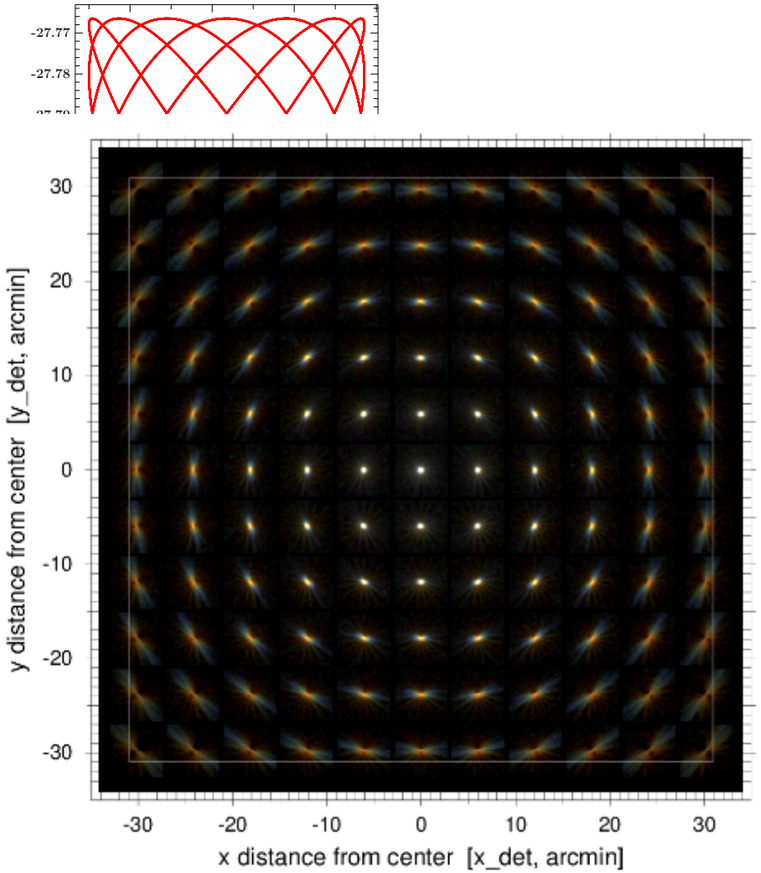

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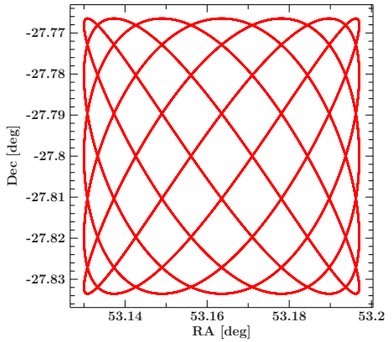

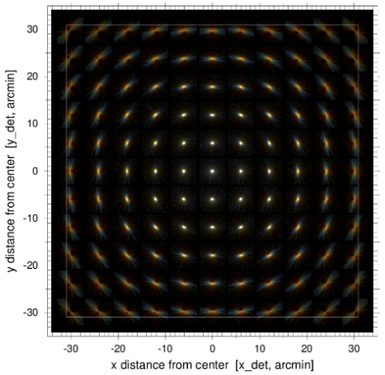

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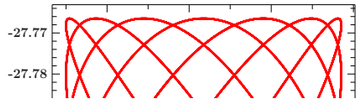

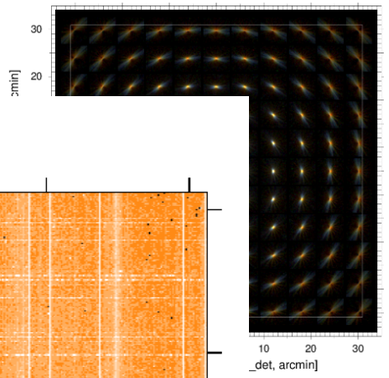

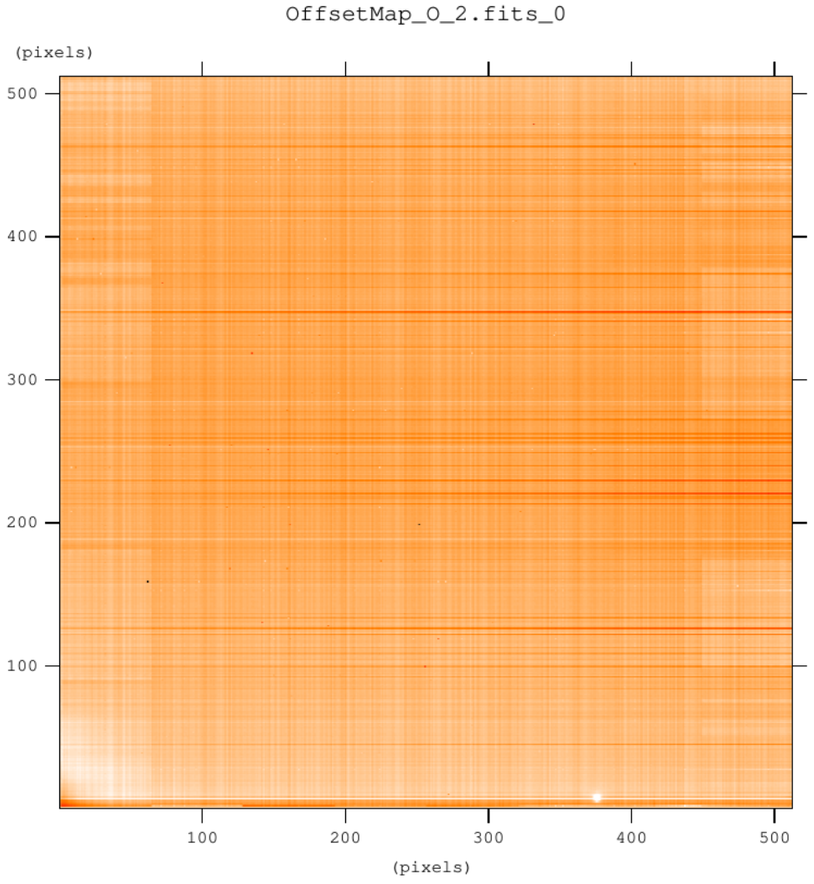

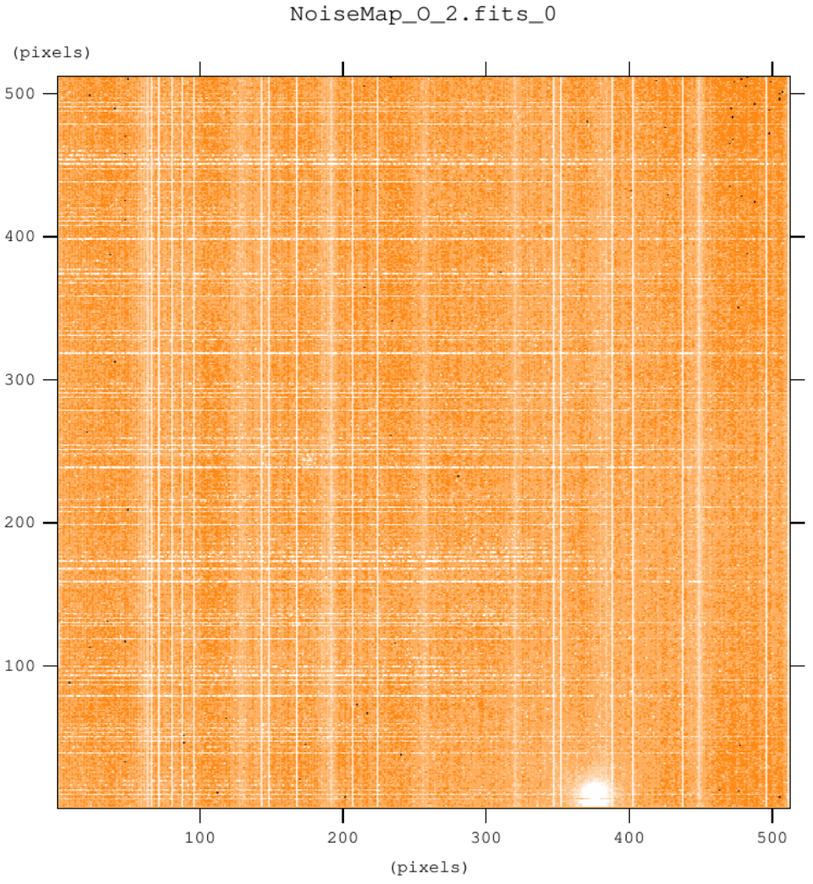

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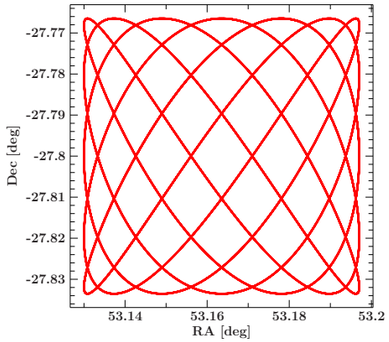

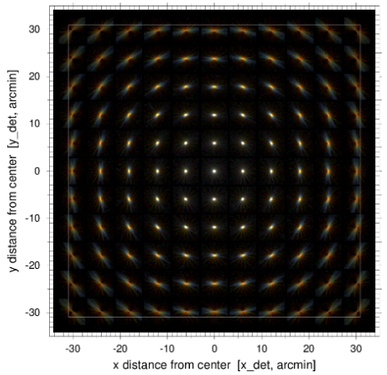

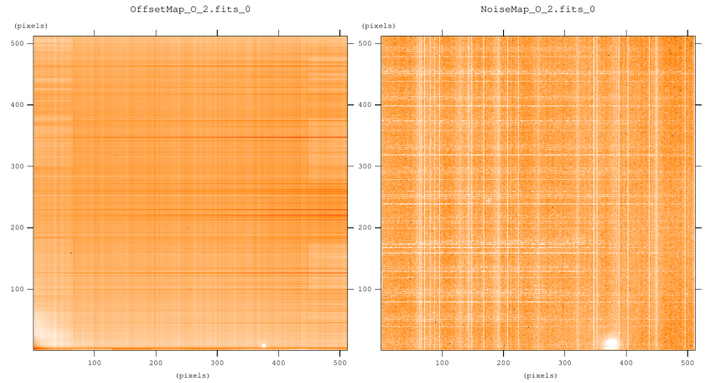

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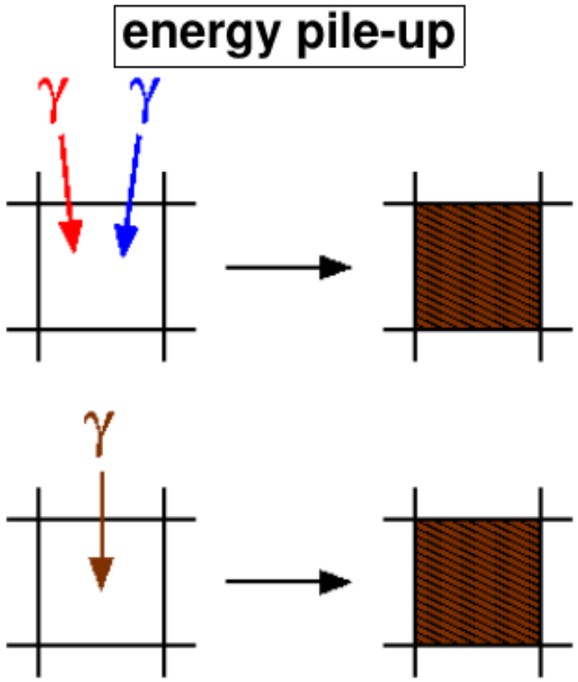

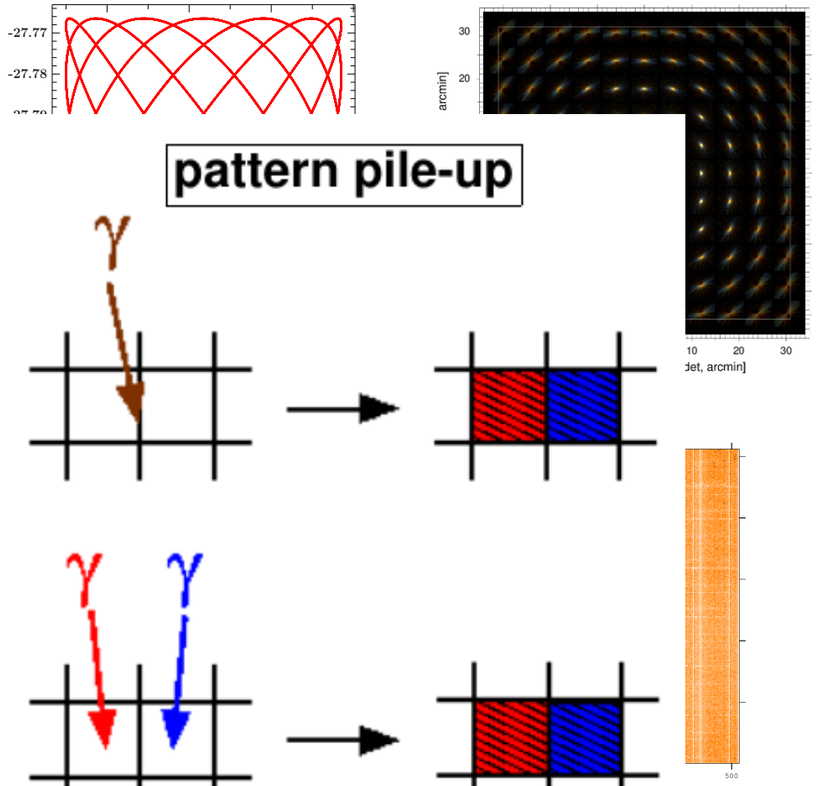

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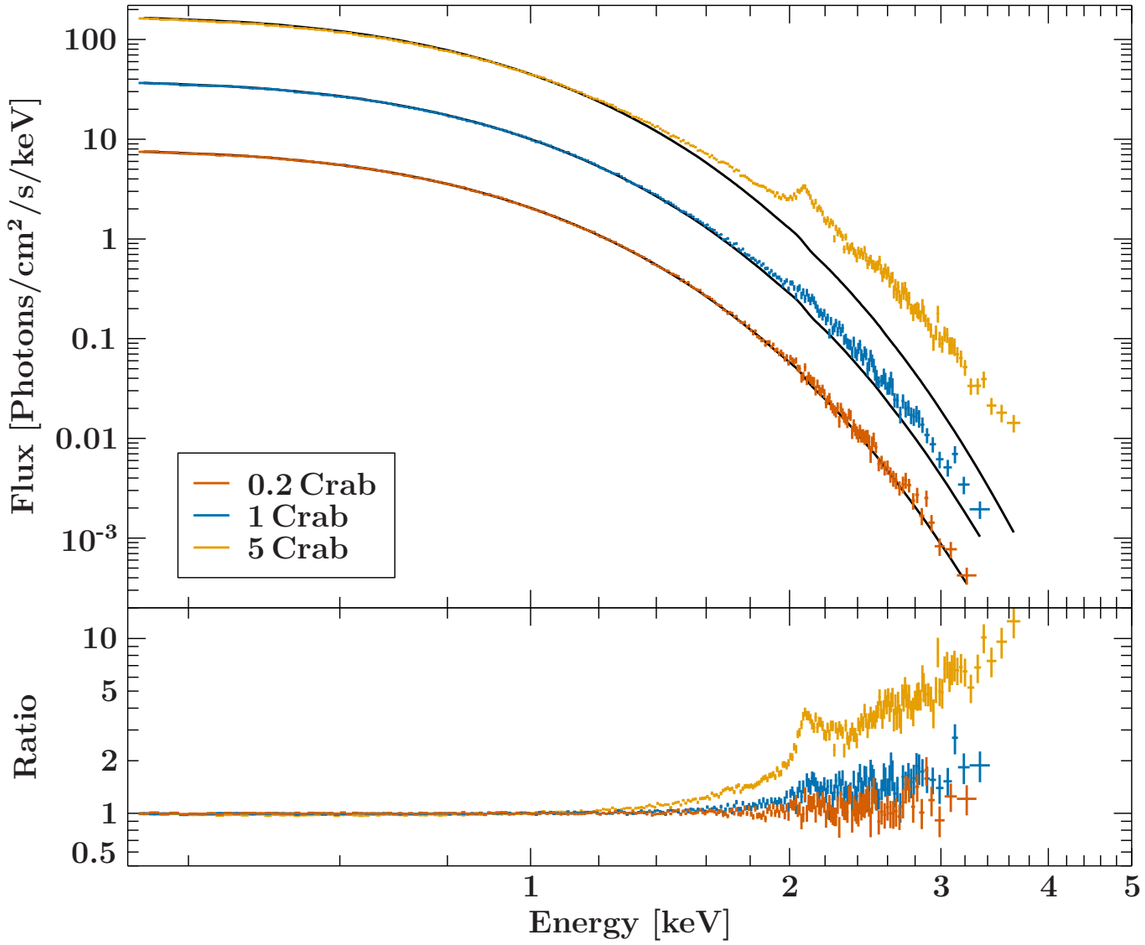

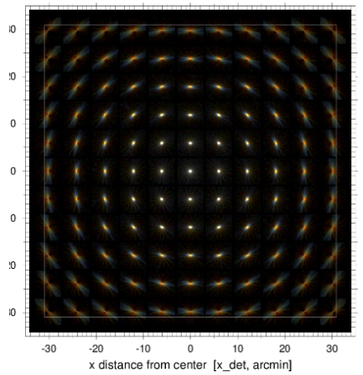

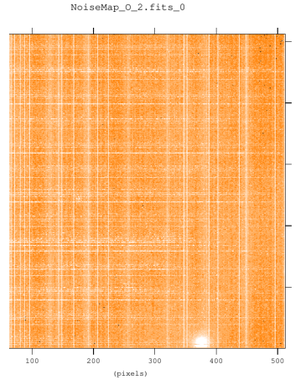

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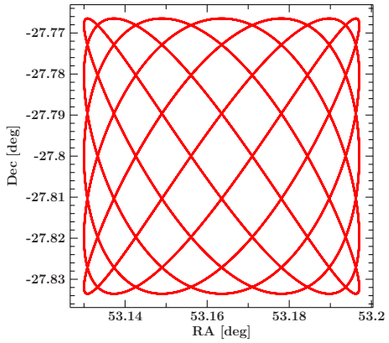

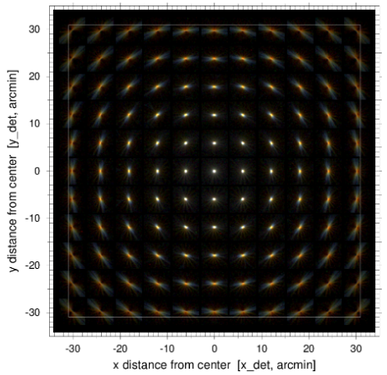

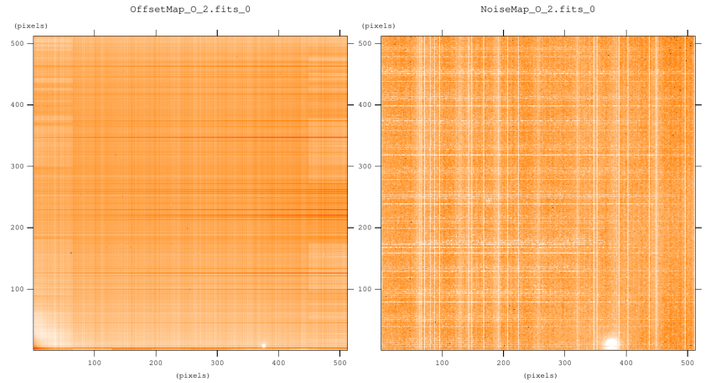

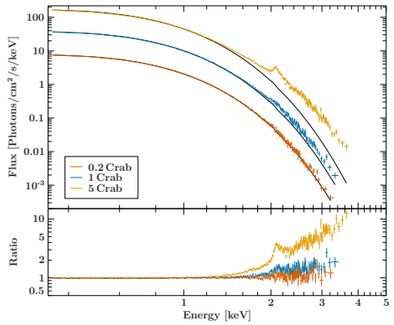

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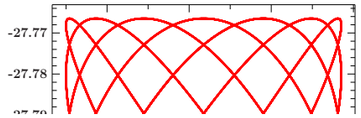
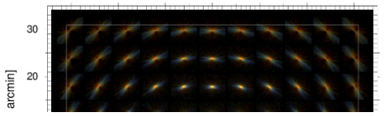
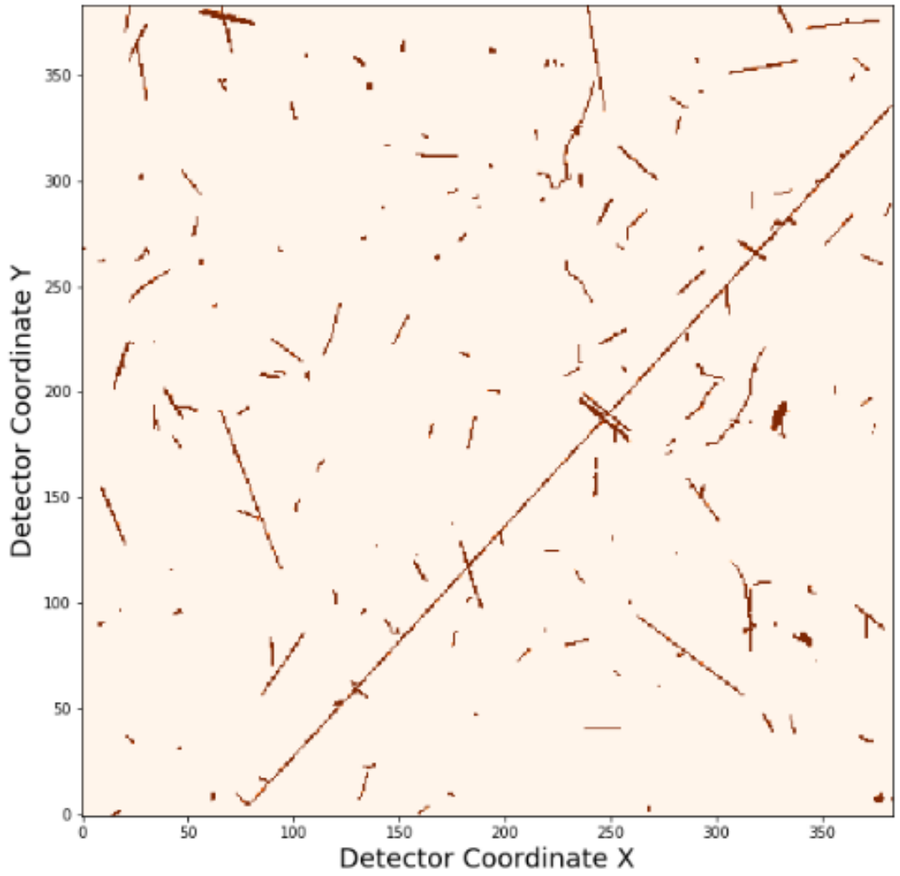
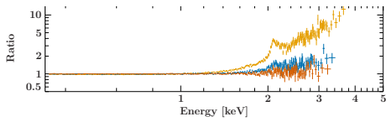
- Particle background

  GEANT interface often needed...









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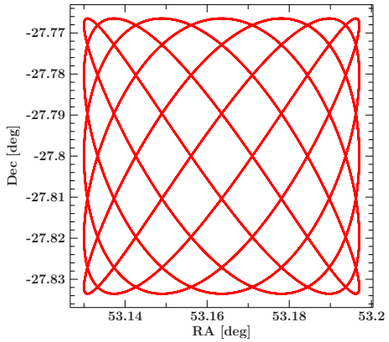
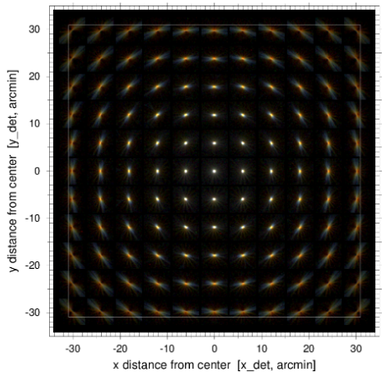
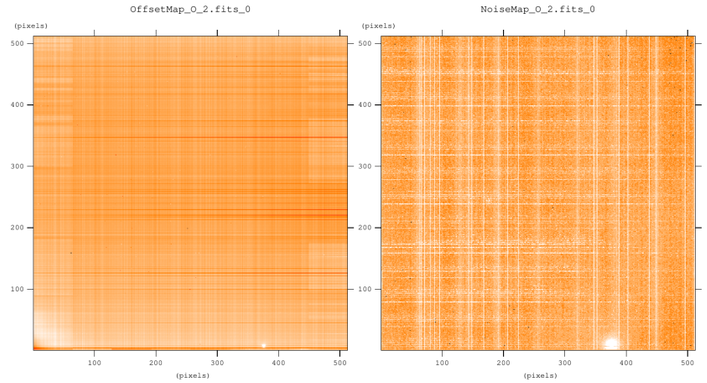
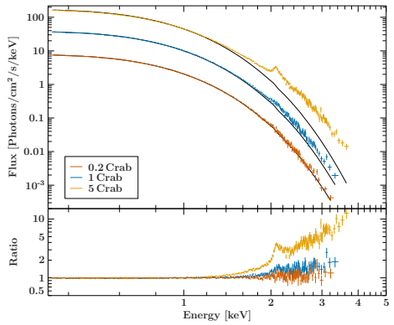
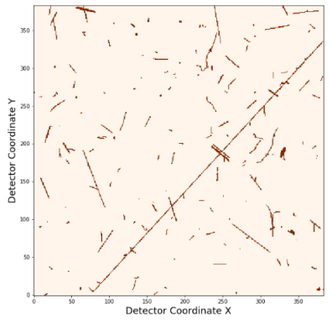








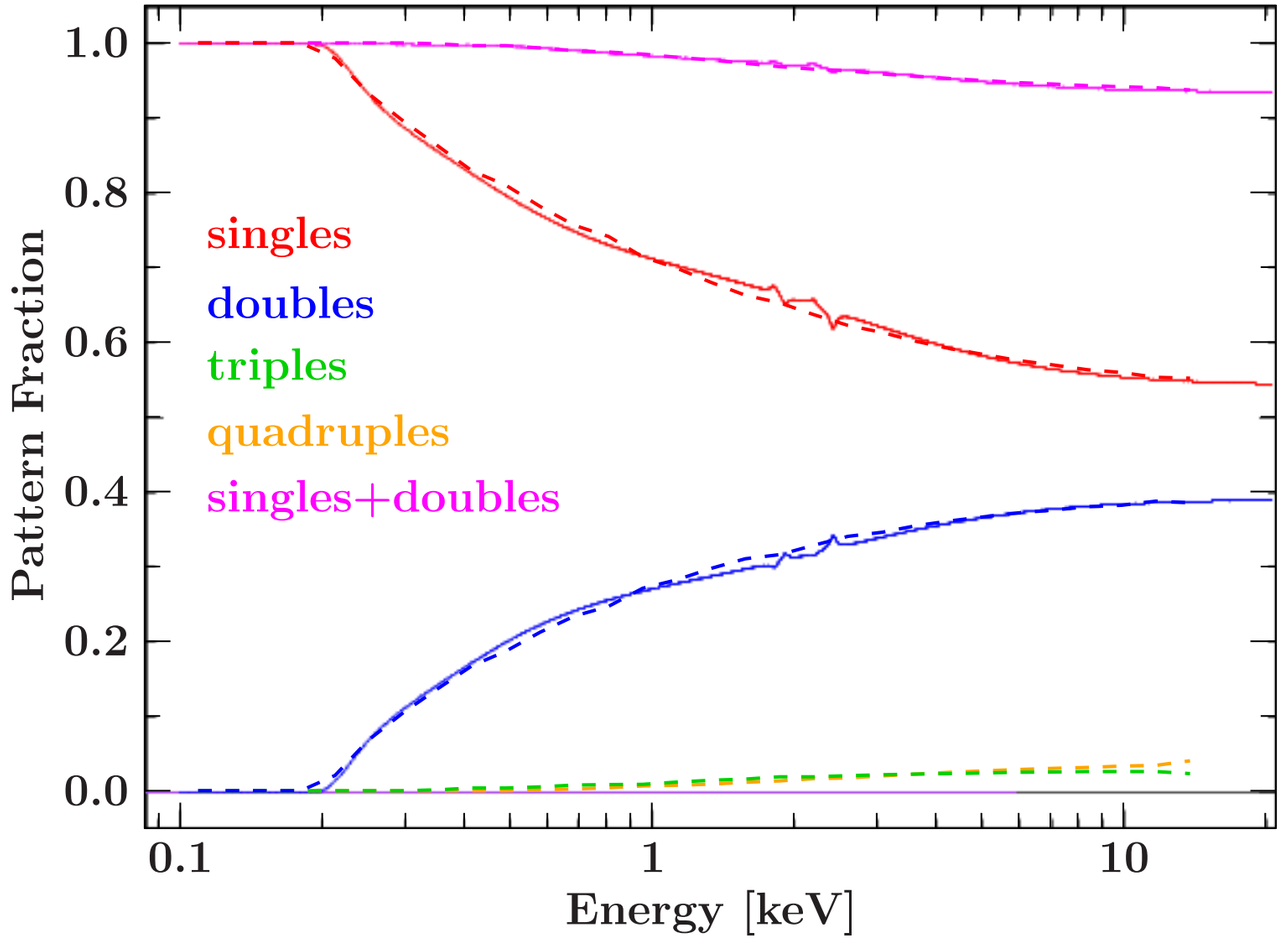


CCD Effects – Patterns and Pileup

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)



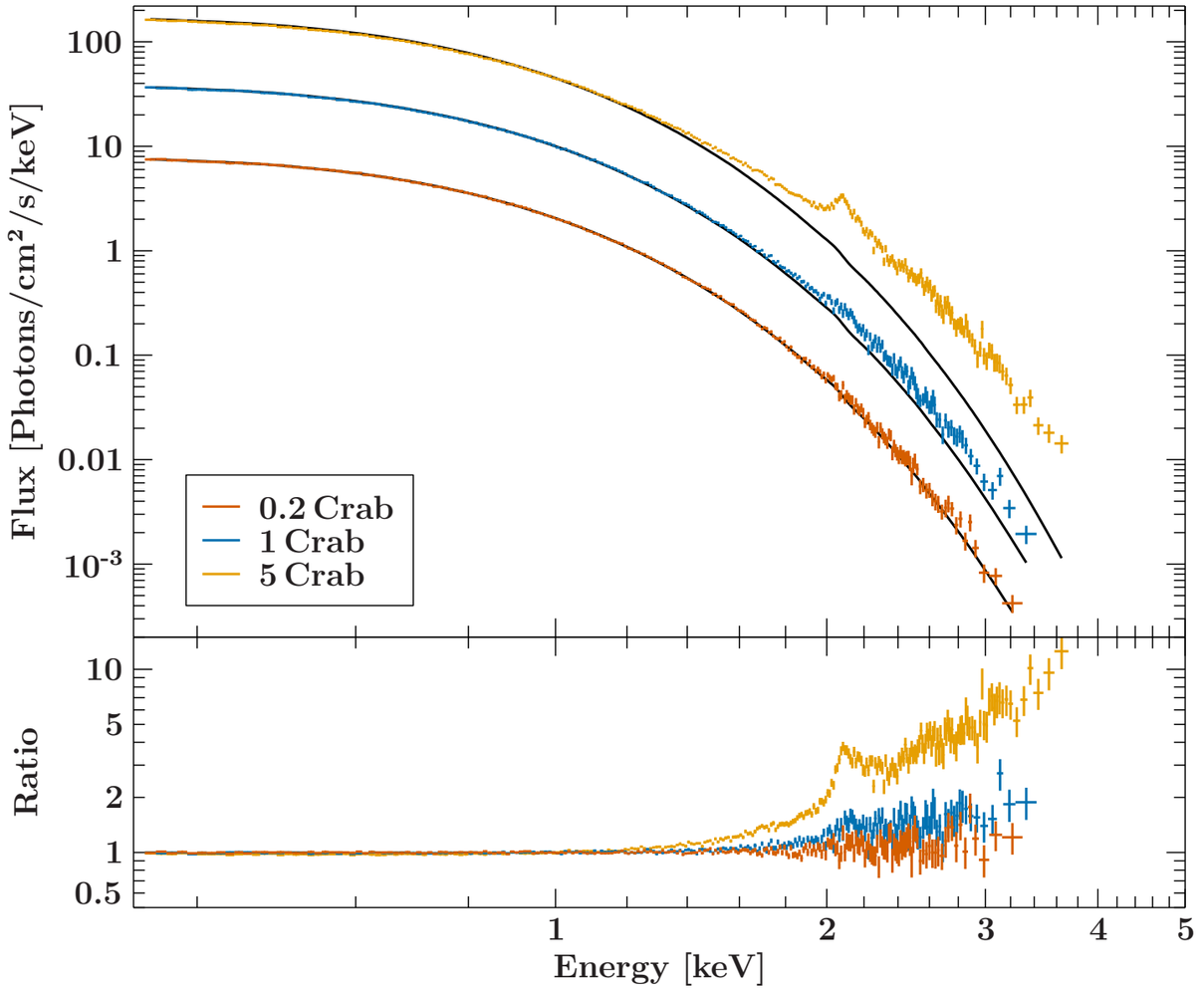
Dauser et al. (2019)

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)

Design considerations

A comment on software design:

Simulators need to survive full mission life-cycle, i.e., realistically for 20 + *x* years

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$\Longrightarrow$ need to use ISO/ANSI standardized languages for simulator kernel, i.e., C, C++, etc., no scripting languages, and best avoid mixing of GUI and simulator kernel

yes, python *is* a scripting language

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yes, python *is* a scripting language

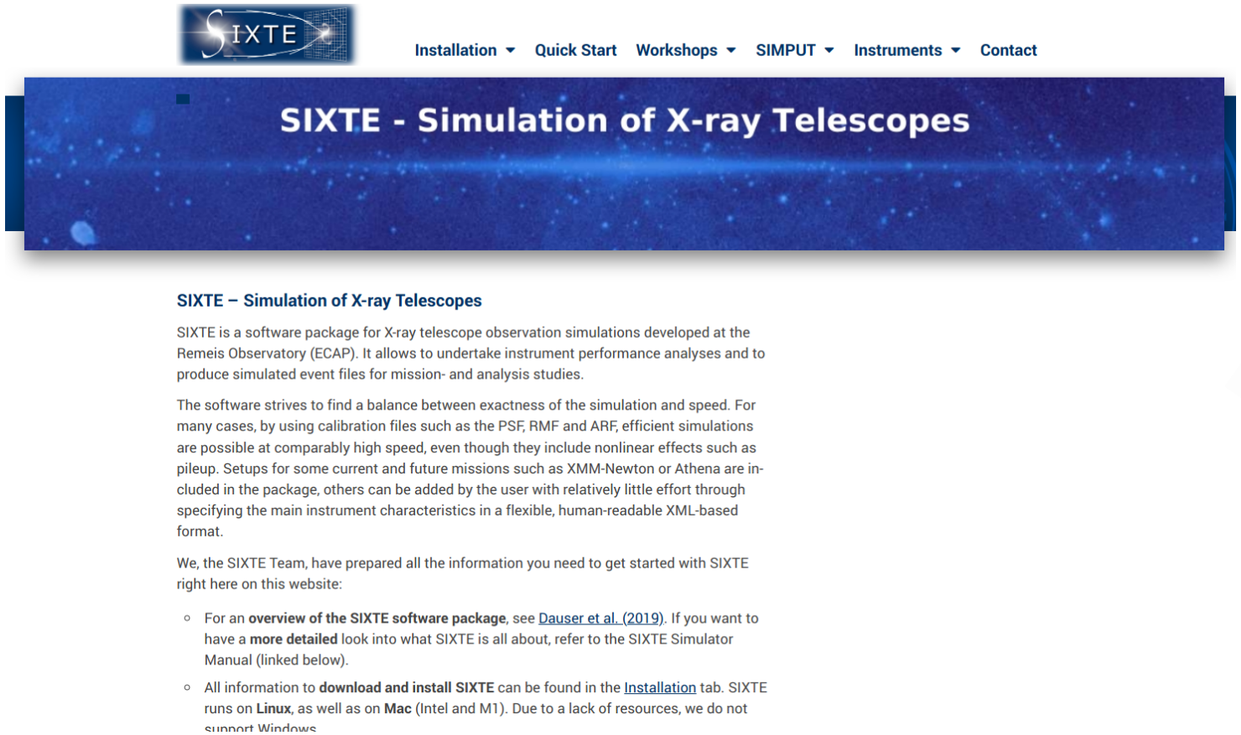
Comments:

- analysis of simulation: scripting languages are fine!
- I disagree with the argument that it's a problem to find people who know C, C++, Fortran et al. – good programmers can (and should!) learn new languages

  The real problem is the algorithms and their complexity, *not* the language in which algorithms are expressed!
- Output: Data that should be analyzable with standard astronomical analysis software (FTOOLS, XMM-SAS, XSPEC, ISIS,. . .)

  avoids need to write dedicated analysis software
- SIXTE includes prototypes for all typical data reduction tasks

SIXTE: further information



Access:

- documentation: ∼100 p. manual and Dauser et al. (2019, A&A 630, 66)
- help desk: sixte-support@lists.fau.de
- Source code: `https://www.sternwarte.uni-erlangen.de/sixte/`.
  Works on Linux and Mac, git and release versions; also available as docker files and on JHU SciServer, ESA Datalabs, Amazon AWS

Current Developments

Current general focus:

- full ray tracing

  in addition to PSF sampling; includes SPOs

- Coded mask simulation and deconvolution

- Further improvement of detector physics

  $\Longrightarrow$ fluorescence, escape peak, Compton shoulder, simplified model for electron transport in Si-detectors

  verified with Athena/WFI prototype measurements and TES measurements, $\sim 10^5$ faster than full blown GEANT

- optical loading

  including a SIMPUT for the whole sky

- modeling of analogue and digital readout

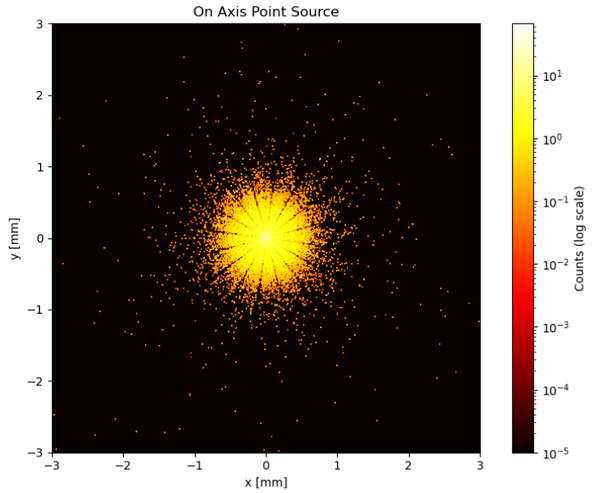
  already parameterized for Athena, eROSITA

- s/w for generation of attitude and orbit files

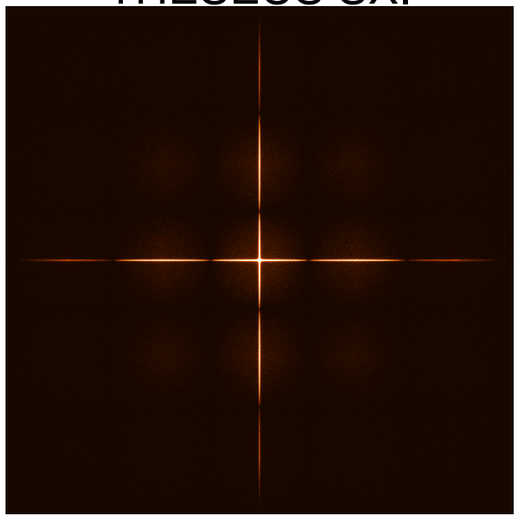
  incl. s/w for modeling uncertainty in reconstruction of these

Current Developments

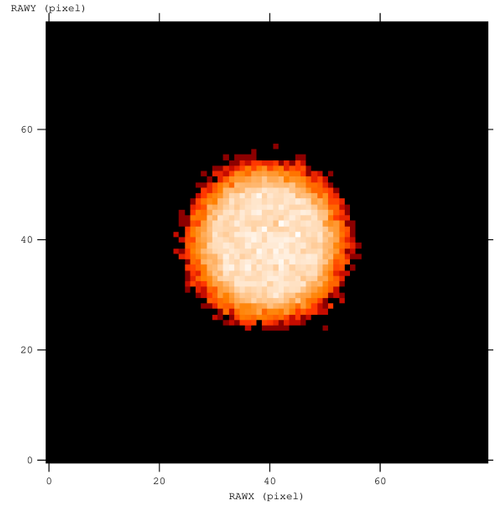
Wolter Optics

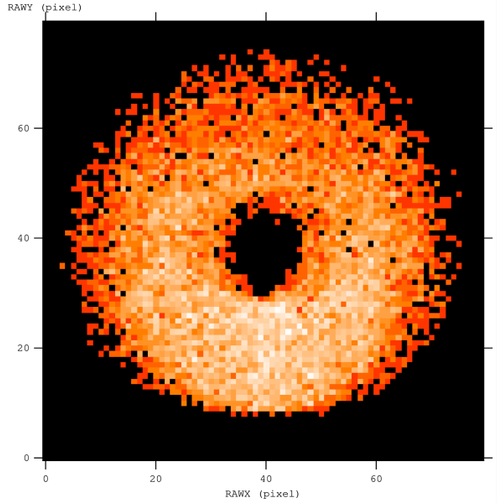


THESEUS SXI

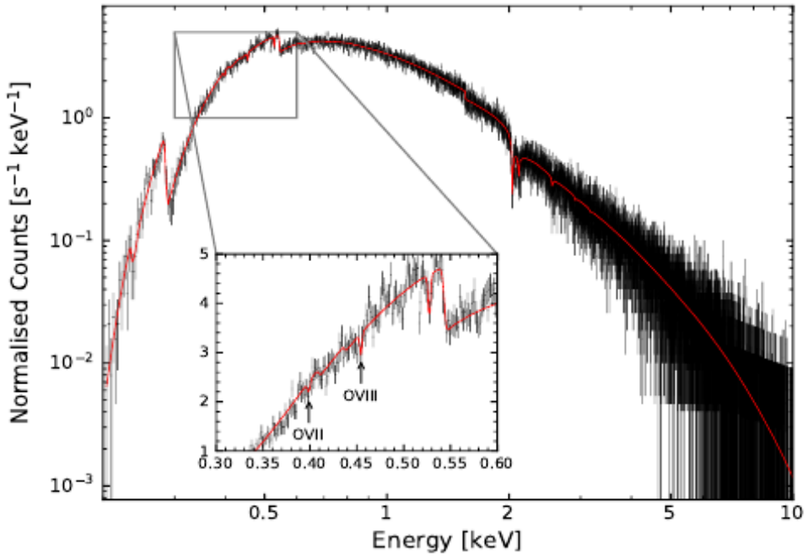


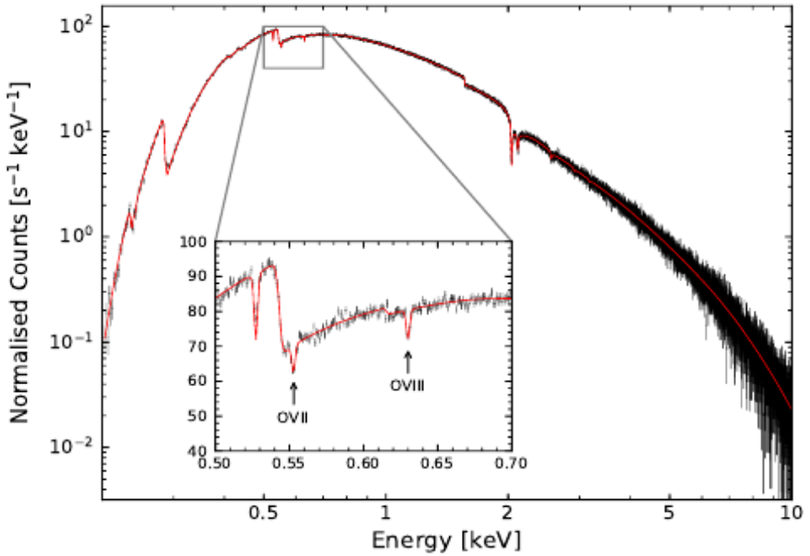
Laue Lens on-axis and off-axis





Example: GRBs and WHIM

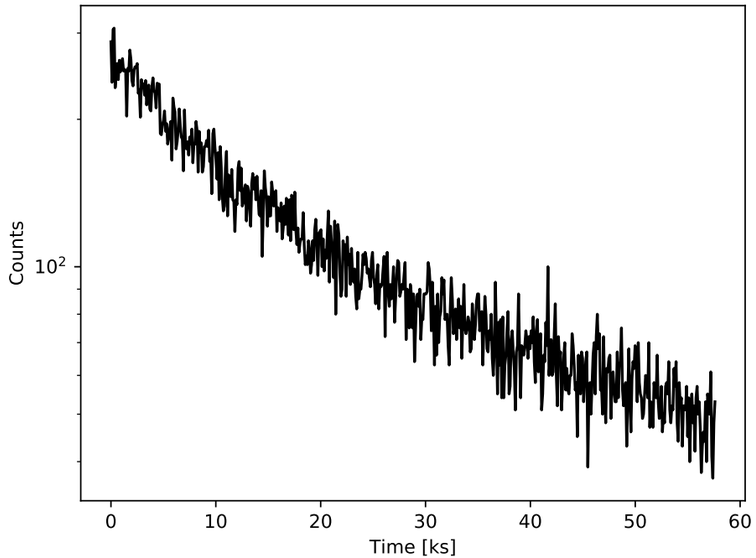




z_{WHIM} = 0.4388

Walsh et al. (2020, A&A 642, 24; GRB is at z = 2)

z_{WHIM} = 0.0382

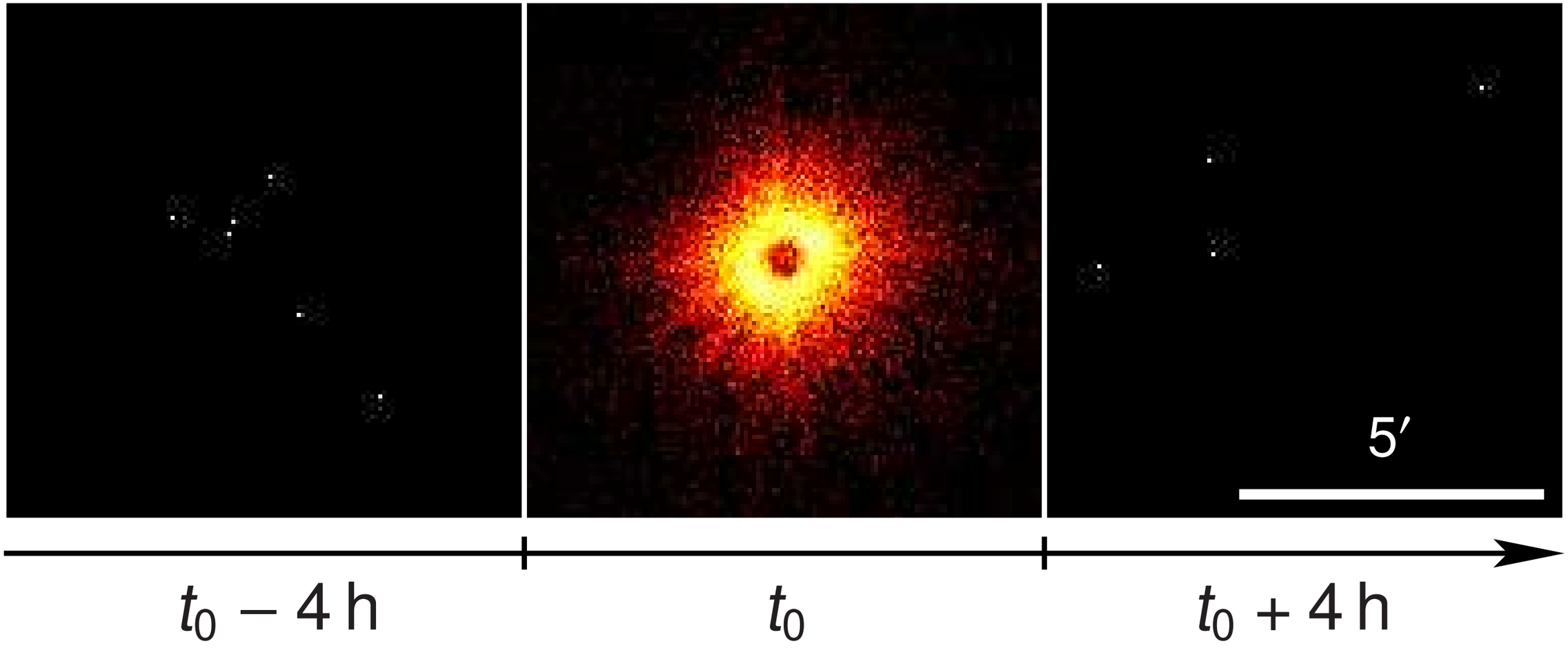


Example: Detection of Oxygen lines from WHIM in GRB spectra

Uses:

- realistic lightcurve
- realistic spectral shape

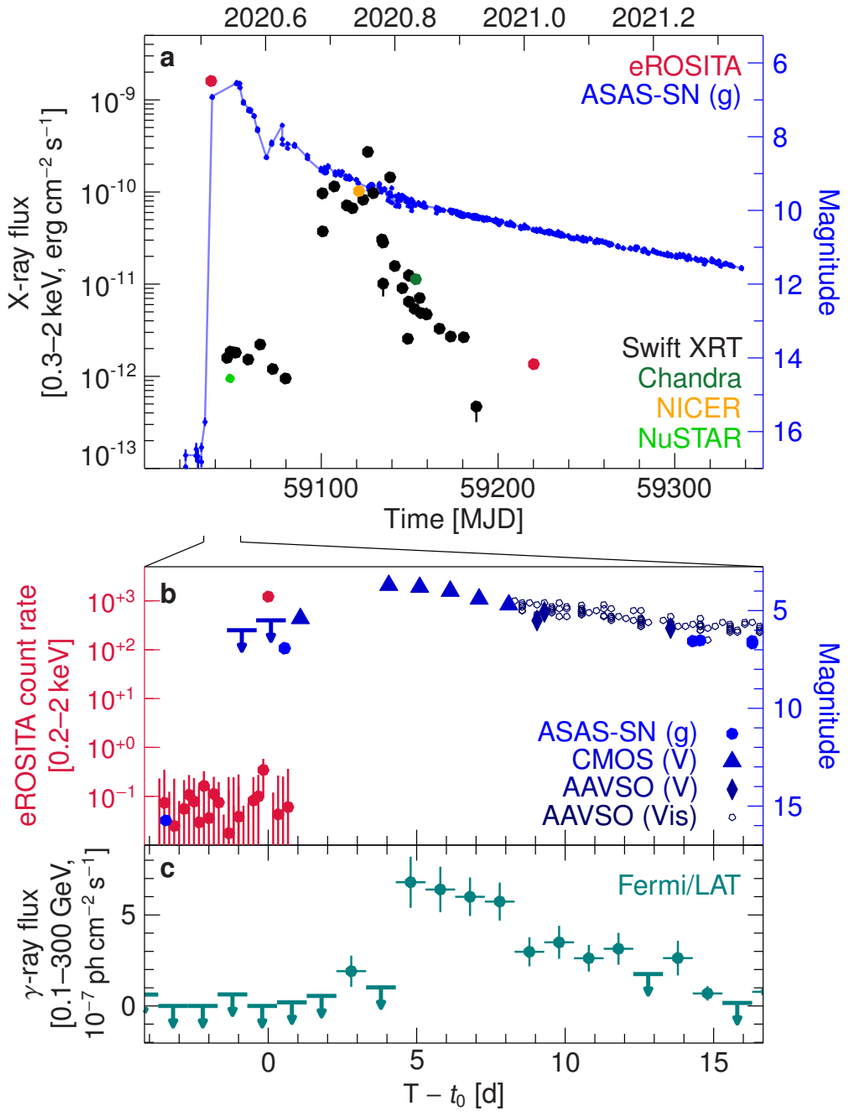
Example: Nova

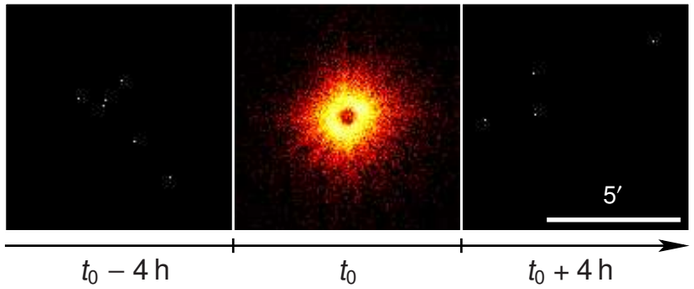


YZ Ret (Nova Reticuli 2020): Extremely bright source seen 2020-07-07, 16:47; no detection 4 h before or after

Example: Nova

König et al. (2022, Nature)



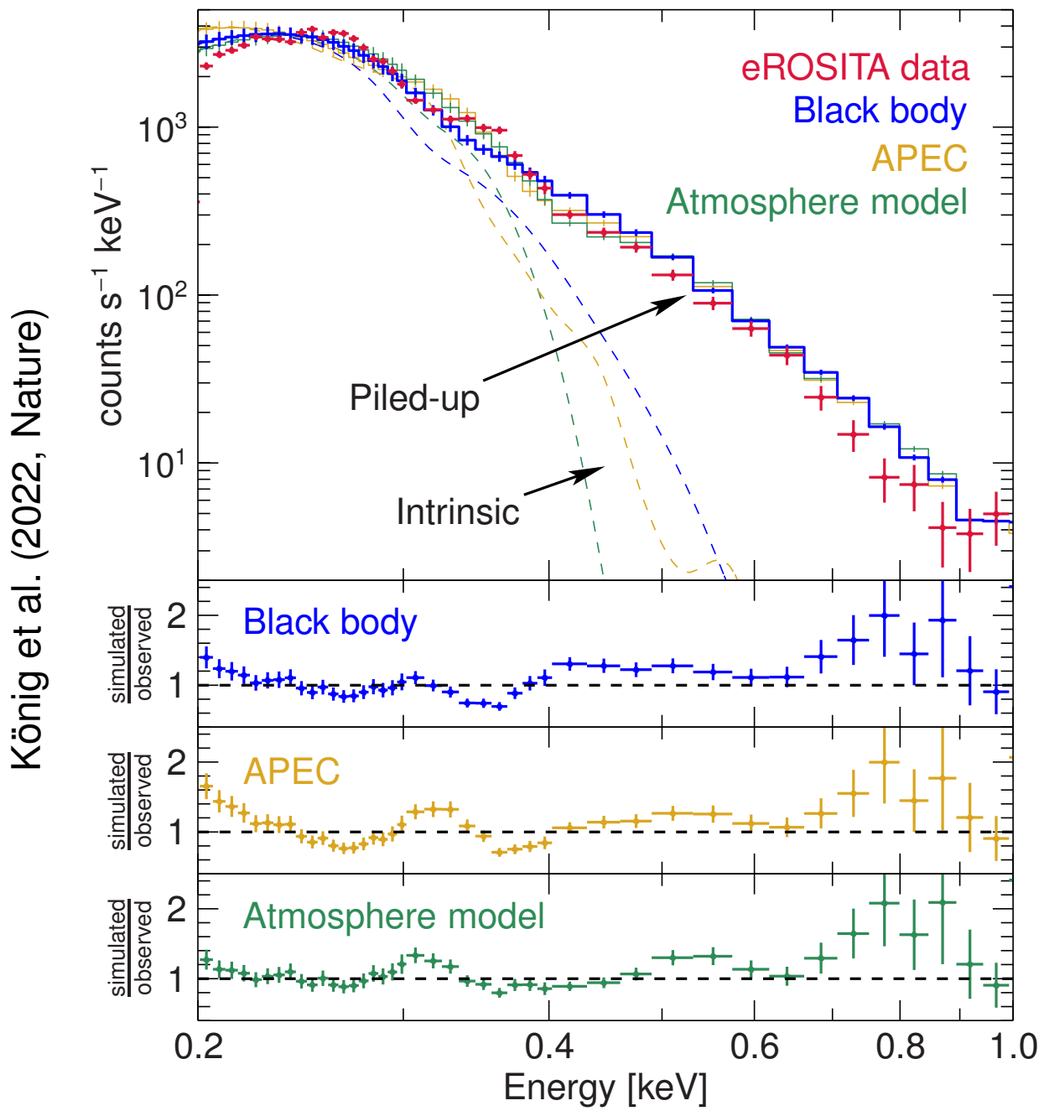


X-ray seen *before* optical

First detection of an X-ray flash

30 yr after prediction (Starrfield et al., 1990).

Example: Nova



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Spectrum "piled up"

($F_{0.2-10\,\mathrm{keV}} = 1.86^{+0.38}_{-0.23} \times 10^{-8}\,erg\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)

Modeling: extremely difficult because of detector effects

- black body

  $kT = 28.2^{+0.9}_{-2.8}$ eV, $L = 2.0(1.2) \times 10^{38}\,\mathrm{erg\,s}^{-1}$, $R = 50000 \pm 18000$ km

- atmosphere model

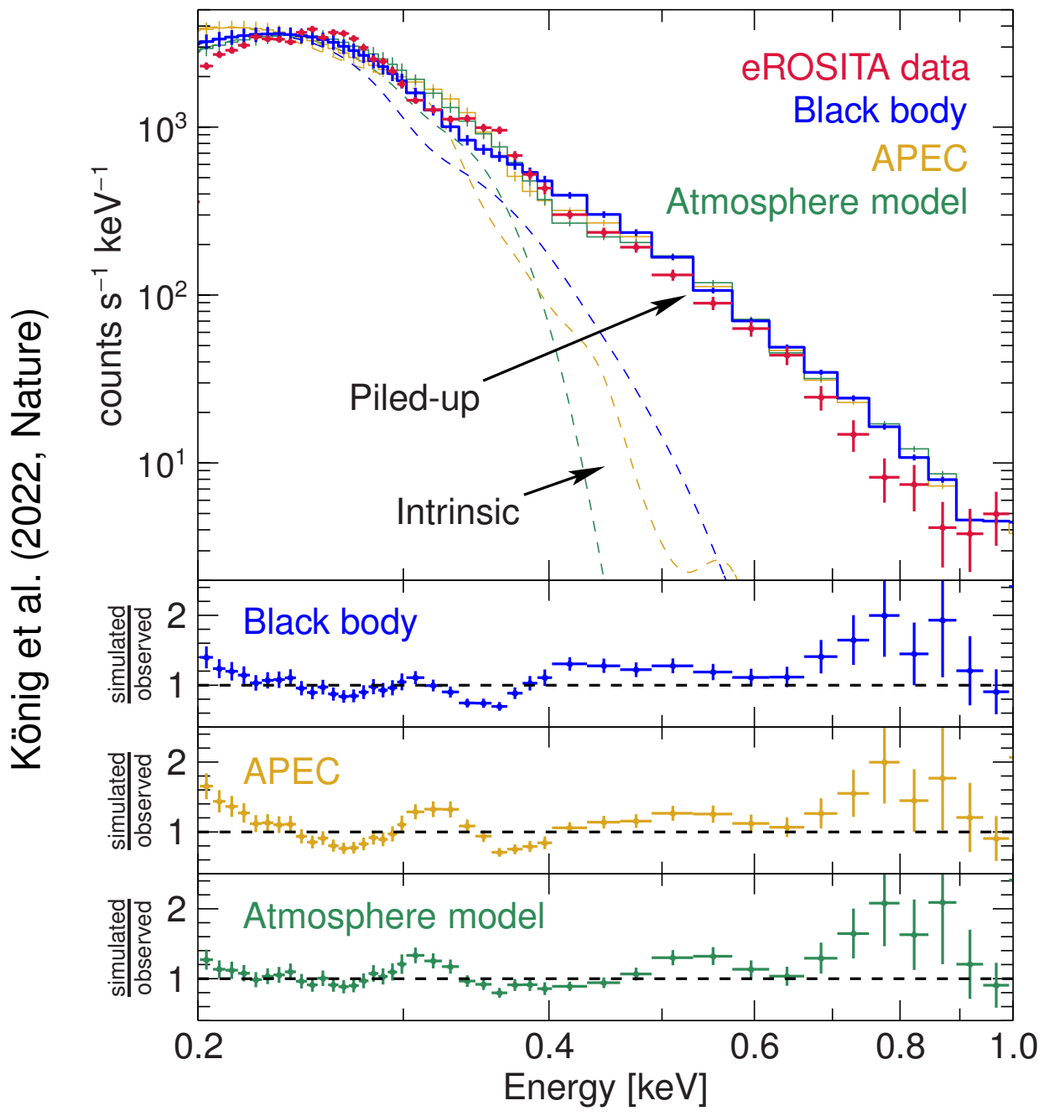
  $kT = 27.1^{+1.2}_{-0.5}$ eV, $L = 0.98(22) \times 10^{38}\,\mathrm{erg\,s}^{-1}$, $R = 37000 \pm 2900$ km, $\log g = 6.97 \pm 0.17$

atmosphere yields

$M_{\mathrm{WD}} = (0.98 \pm 0.23)\,M_\odot$

consistent w/explosion models; Hillman et al. (2014)

Example: Nova



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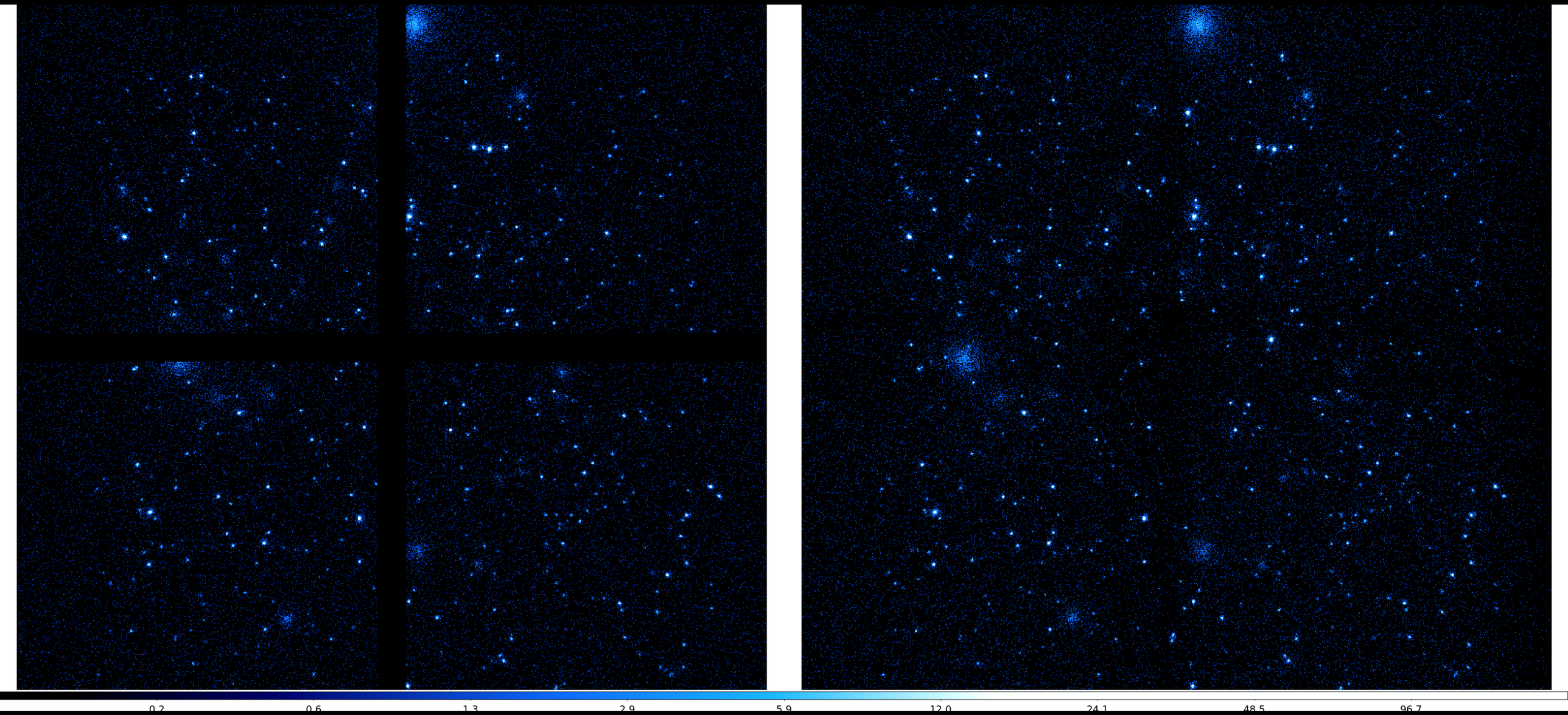
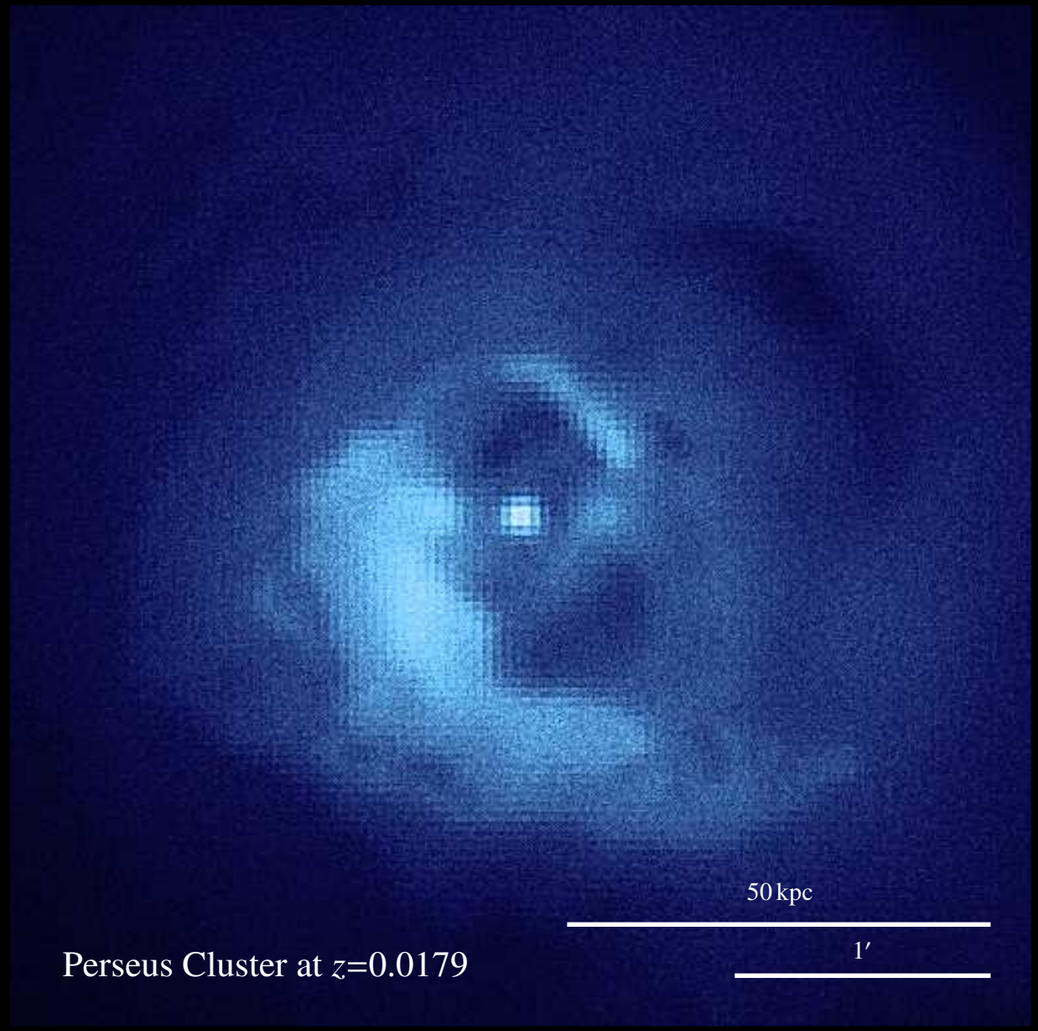


no dithering dithering

5 ks NewATHENA/WFI observation of Chandra Deep Field

Simulation Output



50 ks, one chip

Now shift cluster to higher z:

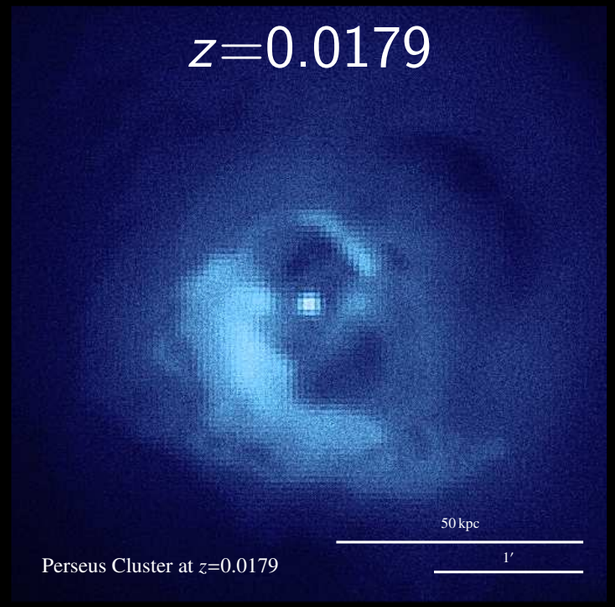
1) Scale cluster size scale via:

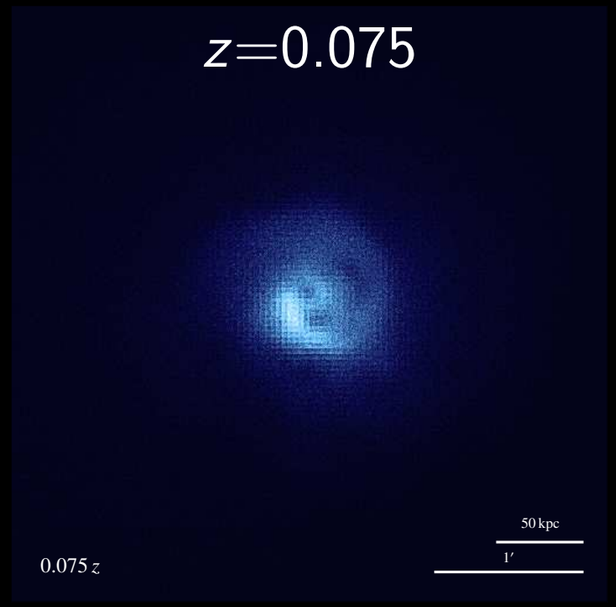
$$\phi(z) = \phi_{\mathrm{pers}} \cdot \frac{D_{\mathrm{pers}}/(1+z_{\mathrm{pers}})^2}{D(z)/(1+z)^2}$$

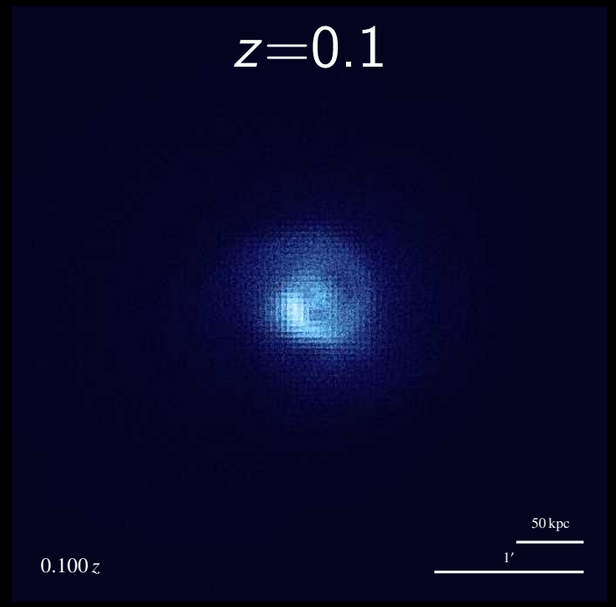
2) Scale flux with luminosity distance:

$$F(z) = F_{\mathrm{pers}} \cdot \left(\frac{D_{\mathrm{pers}}}{D(z)}\right)^2$$

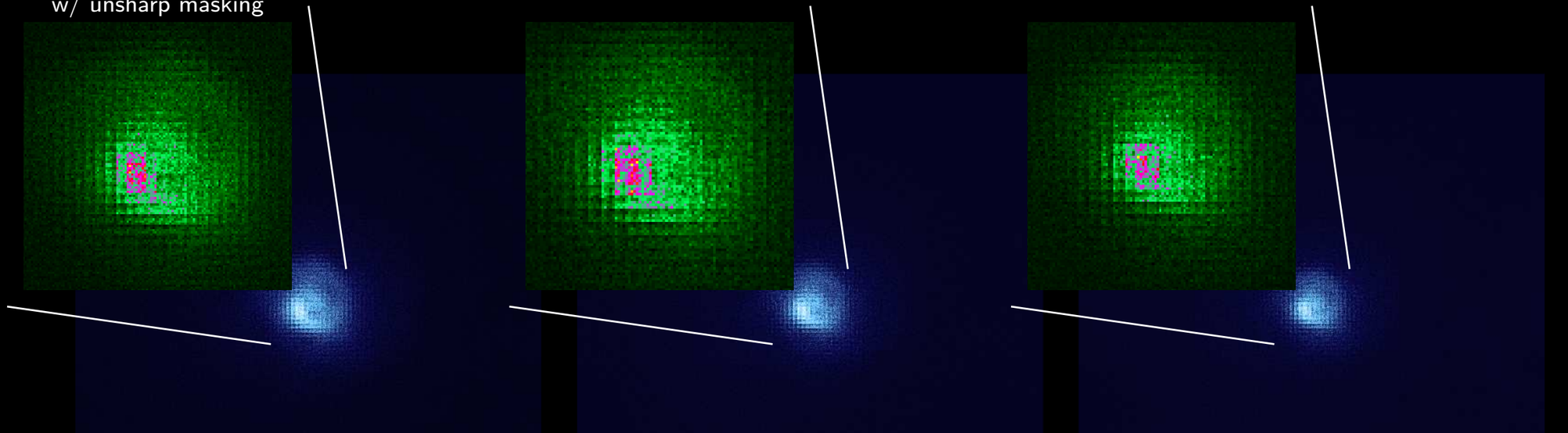
Simulation Output



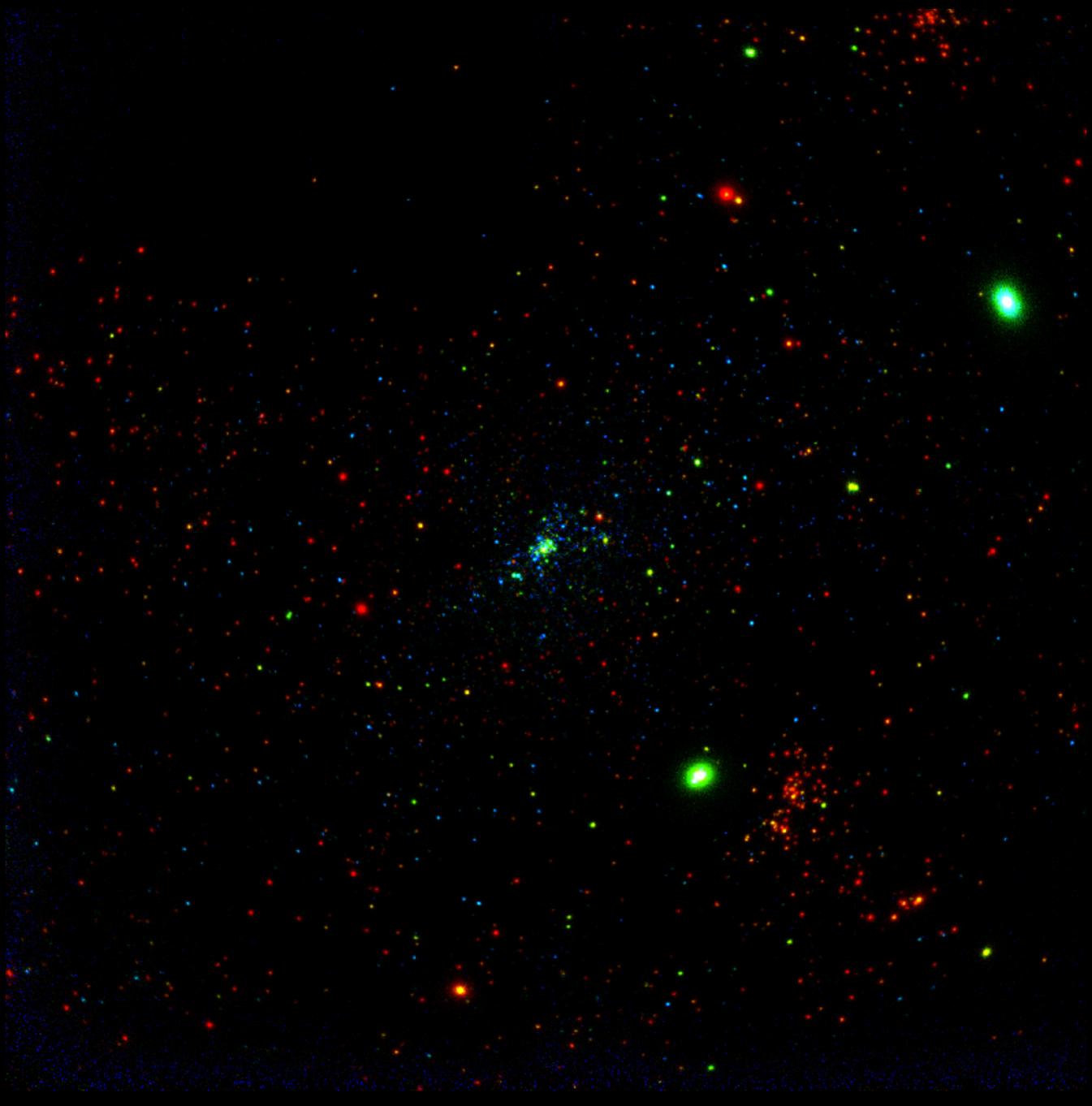


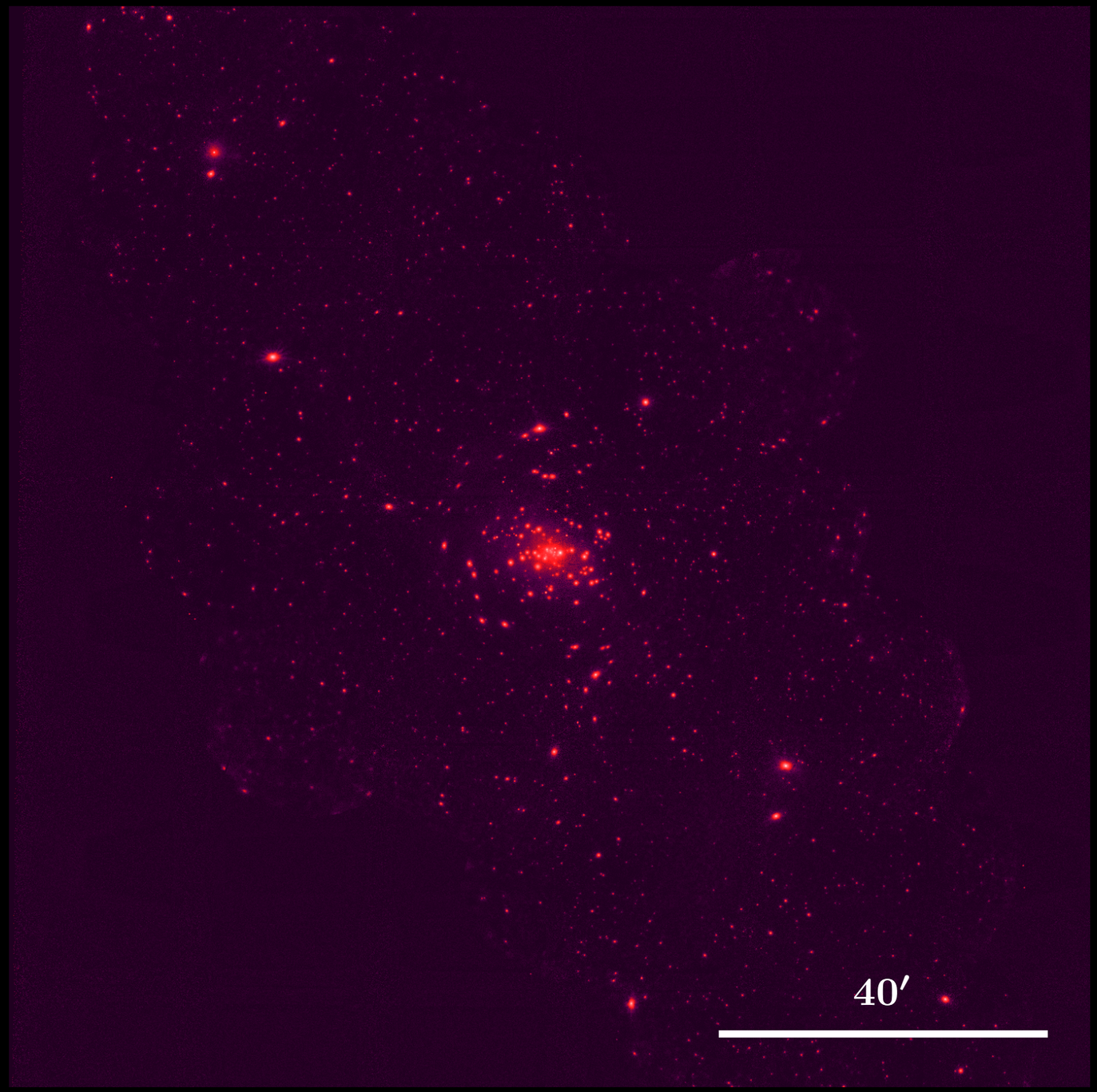


w/ unsharp masking



Galactic Center, BSc M. Rohe (Remeis/ECAP/FAU)





Andromeda, T. Dauser (Remeis/ECAP/FAU), N. Vulic (GSFC)

When to SIXTE?

When not to use SIXTE:

but `fakeit` or similar tools

- fainter point sources ($\lesssim$1 mCrab)

  1 mCrab: $F_{0.5-2\,\mathrm{keV}} = 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$,
  $F_{2-10\,\mathrm{keV}} = 2 \times 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$,

- quick estimates

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- quick estimates

When to use SIXTE:

and *not* fakeit

- bright sources ($\gtrsim$10 mCrab)

  i.e., many “famous” AGN

- faint sources if background behavior or exposure map matters

- imaging simulations:

  galaxy clusters, AGN evolution,...

  - point source detection sensitivity
  - point sources in crowded fields
  - extended sources

- variability simulations

  e.g., reverberation mapping, pulsations, QPOs,...