X-ray spectral fitting in two dimensions

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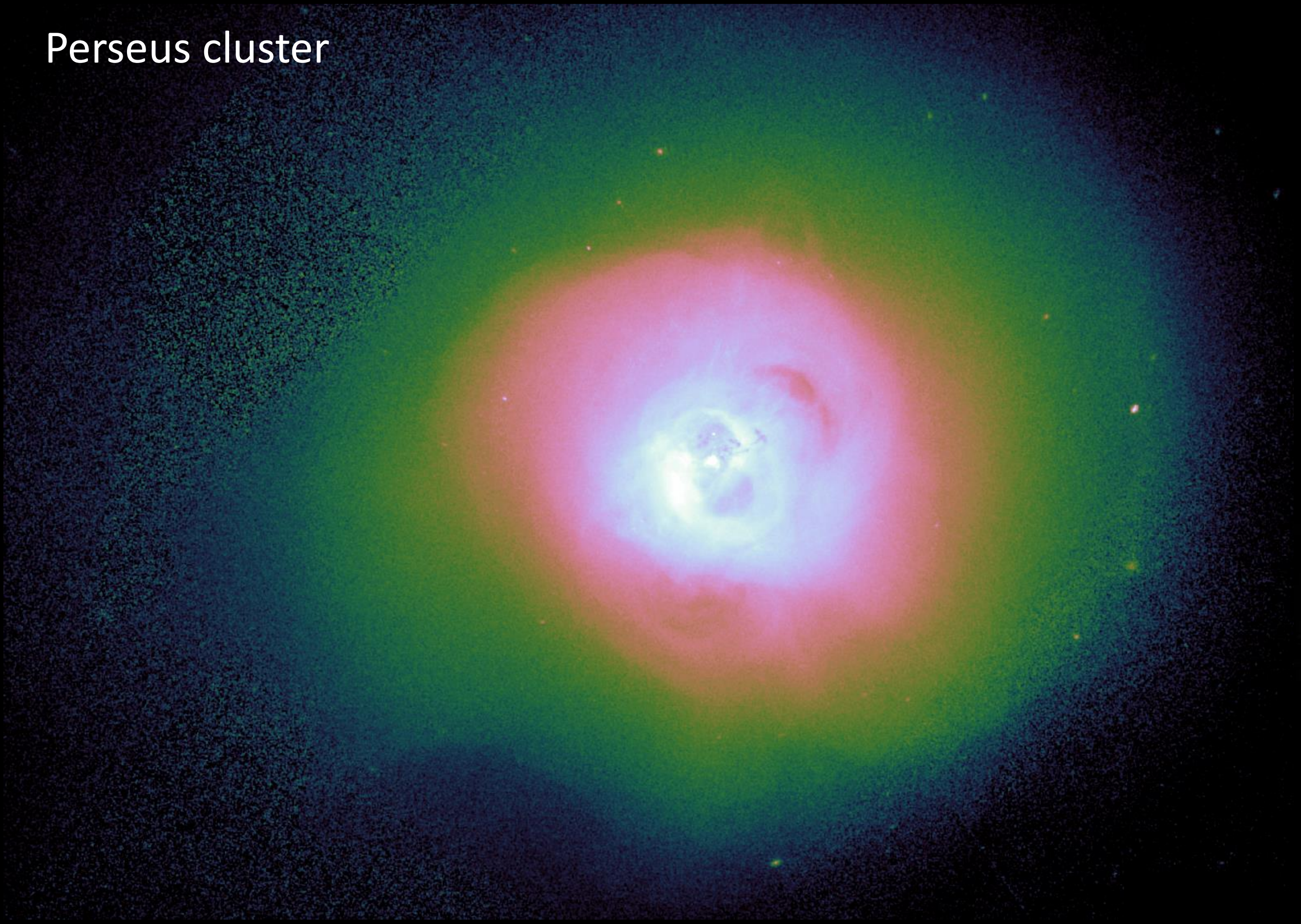
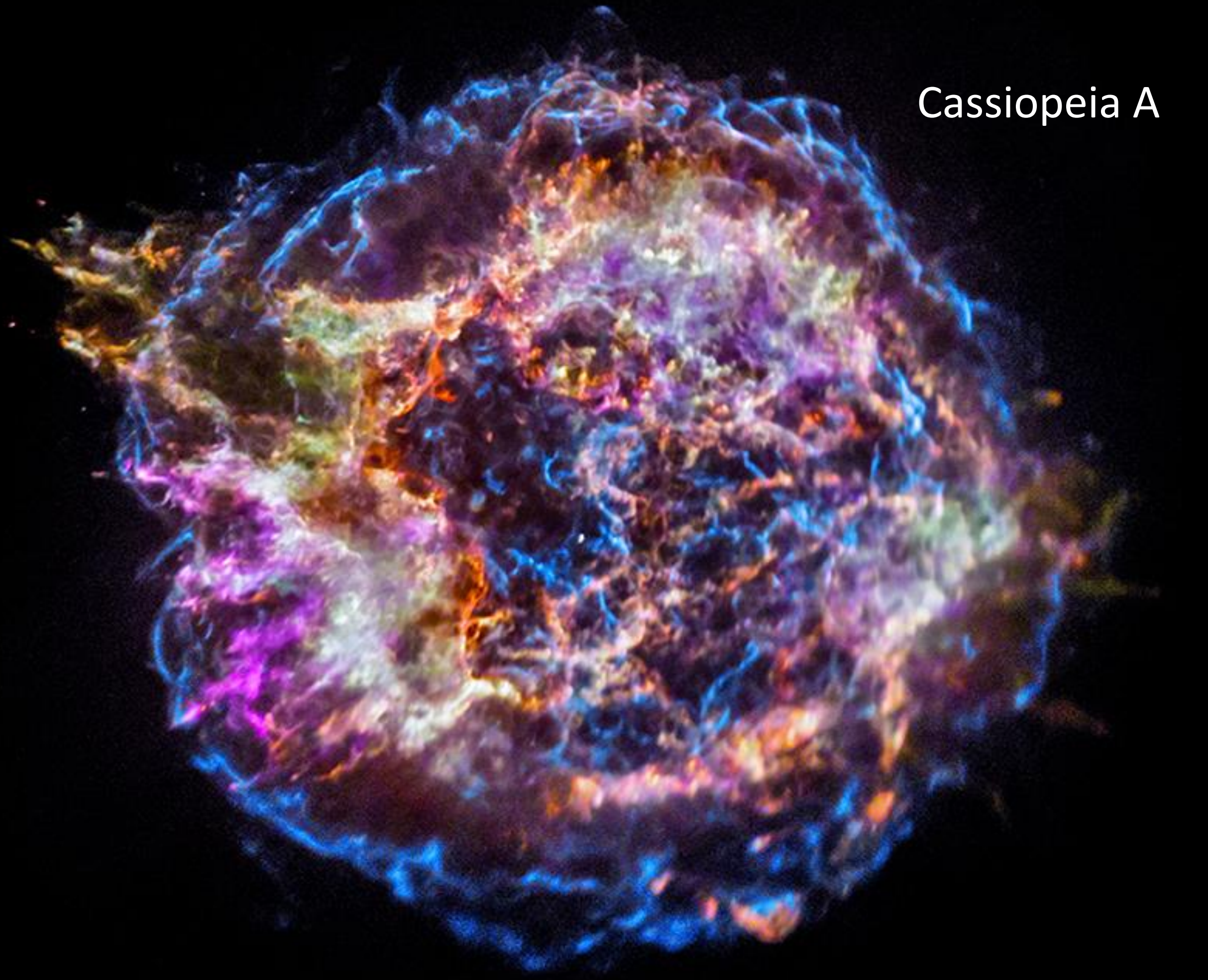
Note: not covering more specialised topics, such as RGS grating analysis

Extended sources can be complex

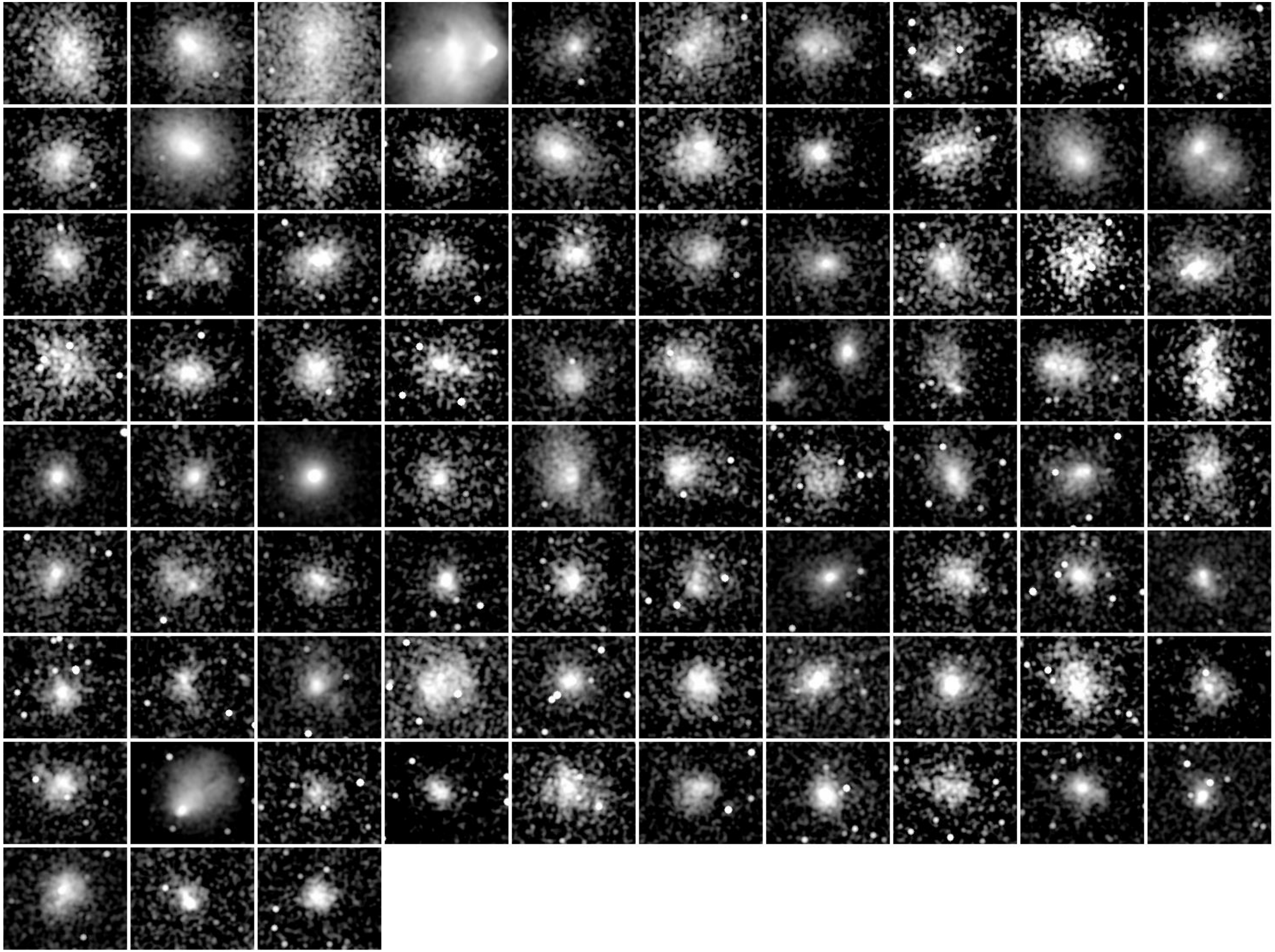
How do you interpret the X-ray data and obtain information about the physics?





Galaxy cluster: want temperature, metallicity, density, pressure, entropy, (velocities)…

Supernova remnant: metals, ionization timescales, velocities…

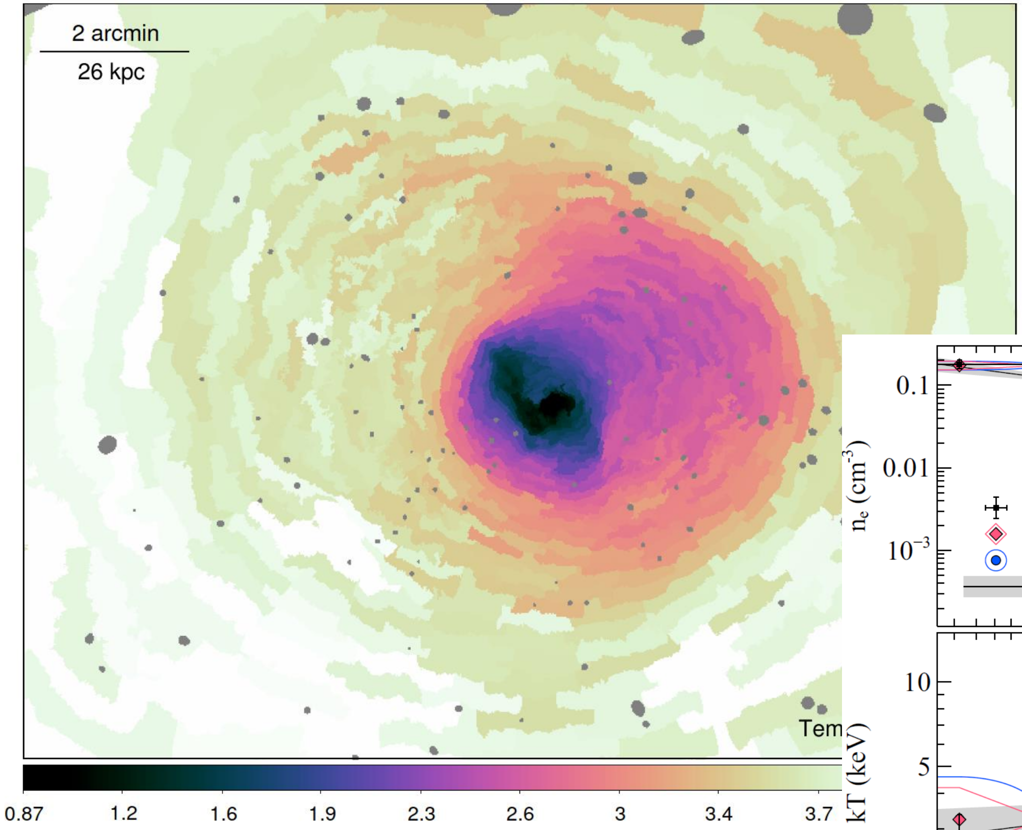


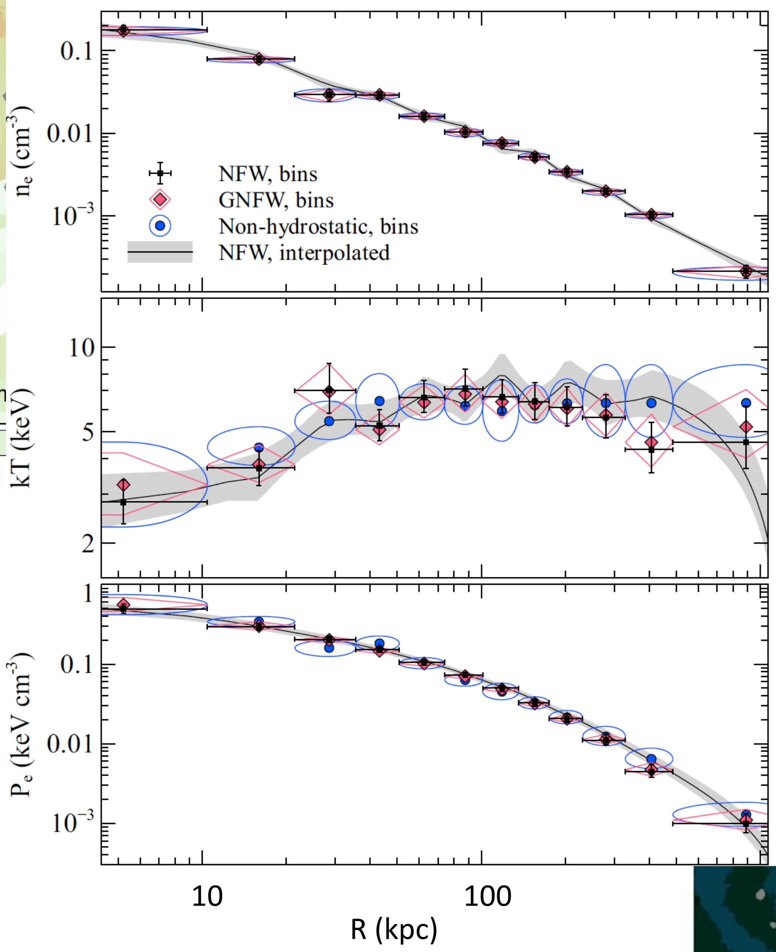
Data quality often poorer!

SPT sample of clusters observed by Chandra

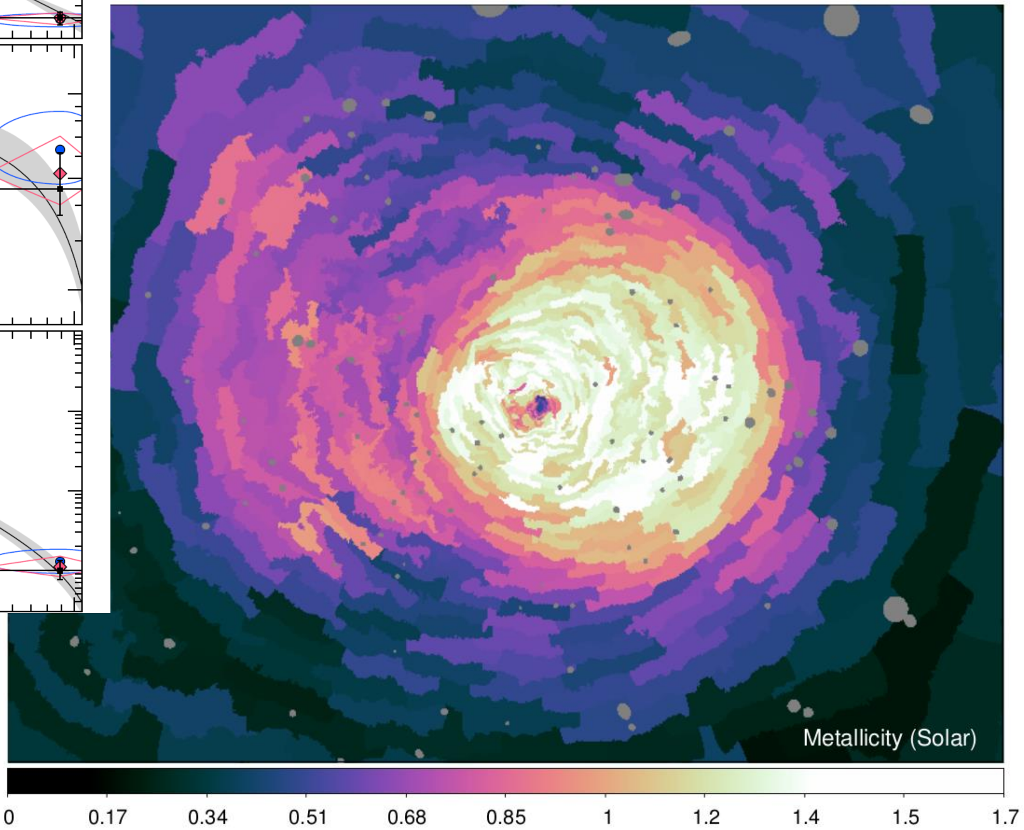
For eROSITA, the typical cluster or group will have many fewer counts than this

Would like maps and profiles of relevant physical quantities





Often no unique way to do this, unless you have a realistic 3D model!



Results are sets of maximum likelihood best fits!

Take care when fitting other models to them, particularly for deprojected profiles

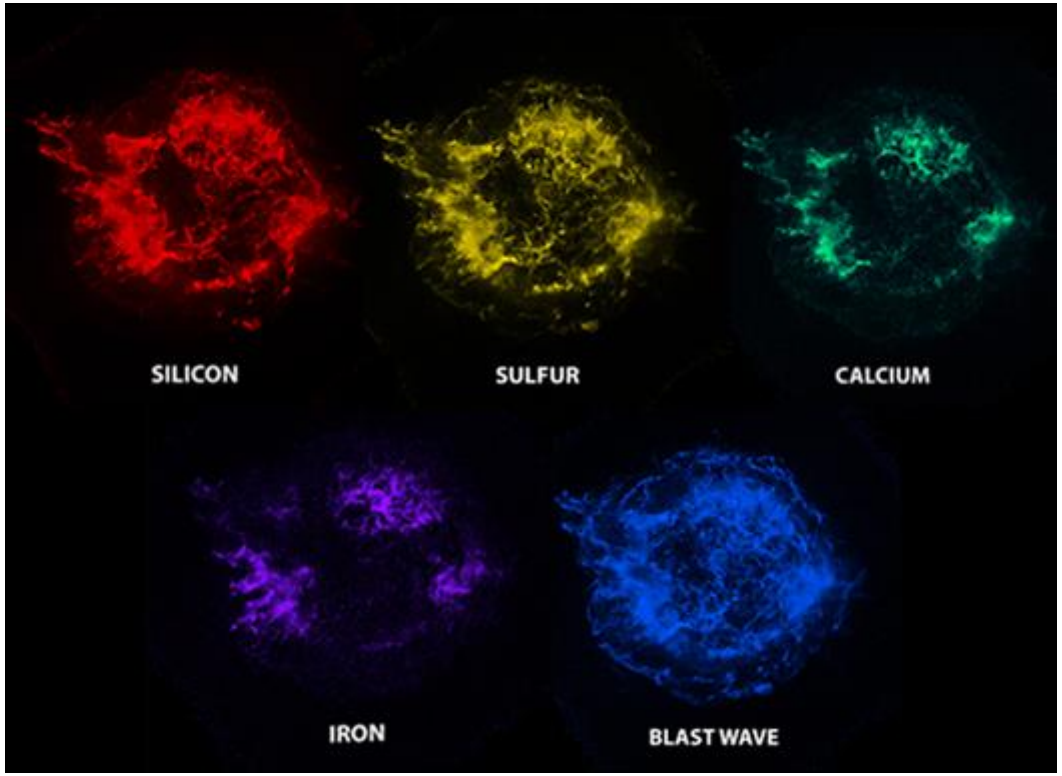
Problems in interpreting 2D data

- How do you choose which regions to examine, or do you try to fit some sort of global 3D model?
- Do you want maps or radial profiles?
- How do you account for 3D→2D projection?
- Which models do you fit? (model selection)

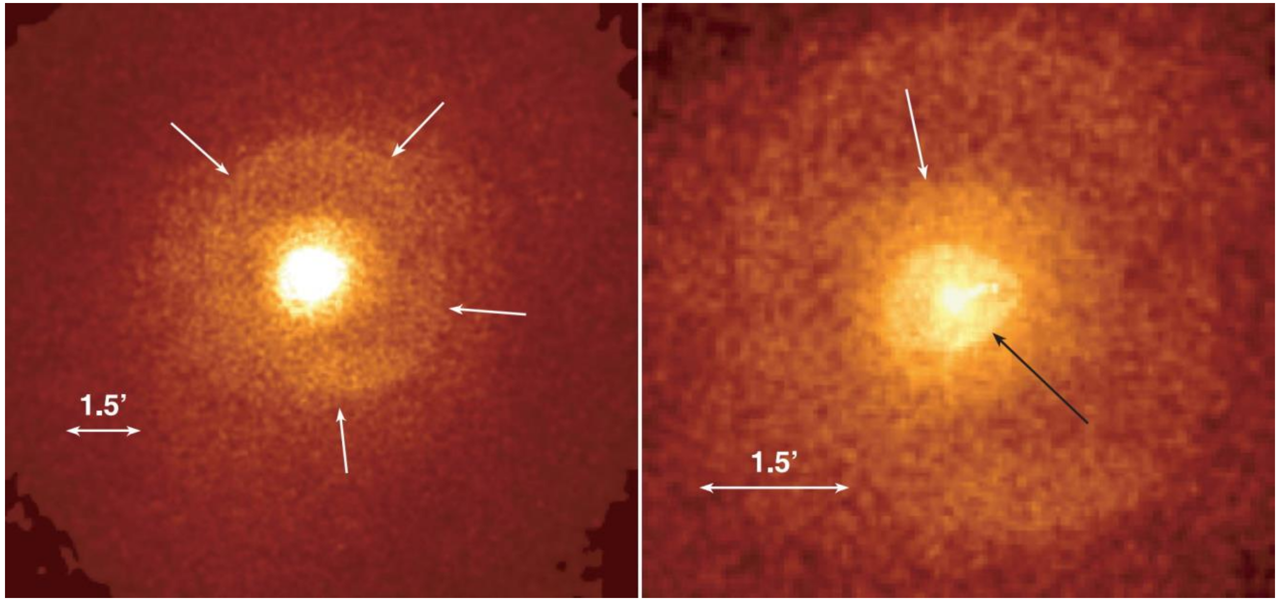
- Instrumental or modelling issues
  - PSF, background, vignetting, response, chip gaps
  - Point source removal / modelling

Avoid spectral fitting altogether?

- Make narrow- or appropriate-band images to examine physics
- In future likely more common-place (e.g. X-IFU on Athena)



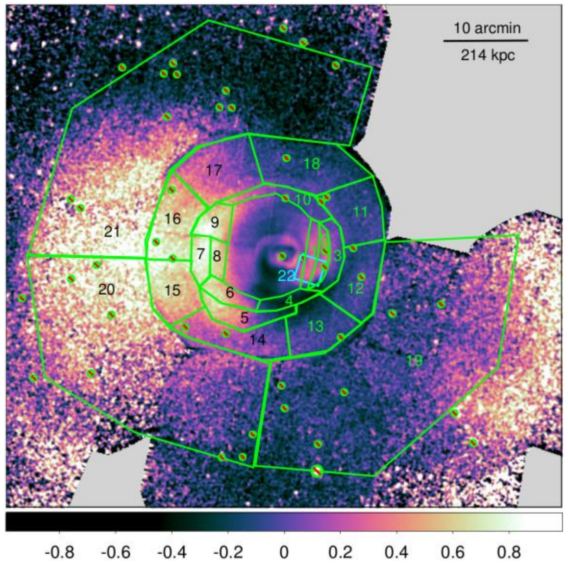
Narrow band images of Cas A (Chandra web site)



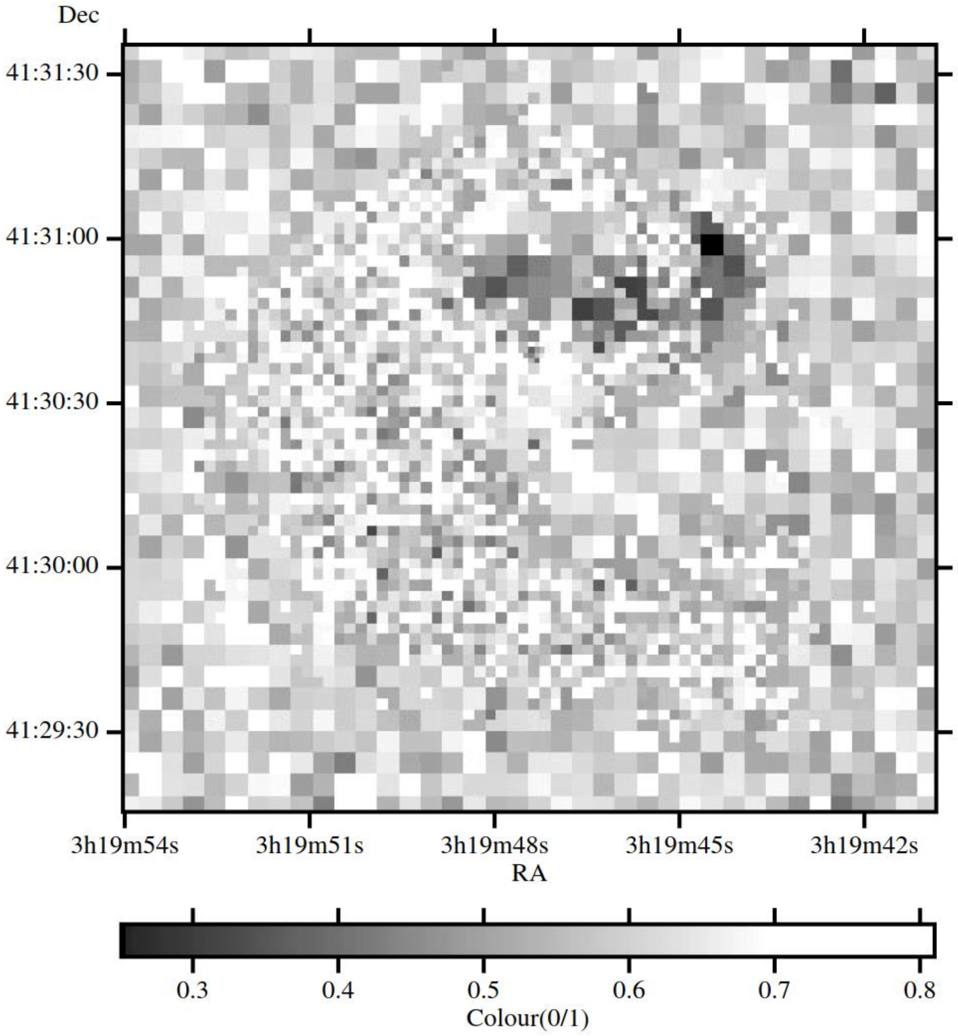
High-energy pressure-sensitive image of M87 (Forman et al. 07)

Region choice

- We want to do spectral fitting and make 2D maps
- What regions do we choose?
  - Independent spatial regions – e.g. choose by hand, adaptive binning, Voronoi tessellation, contour binning…
  - Overlapping regions
- Independent regions are easier to compare
- We can extract spectra from each region, fit and create maps from the parameters

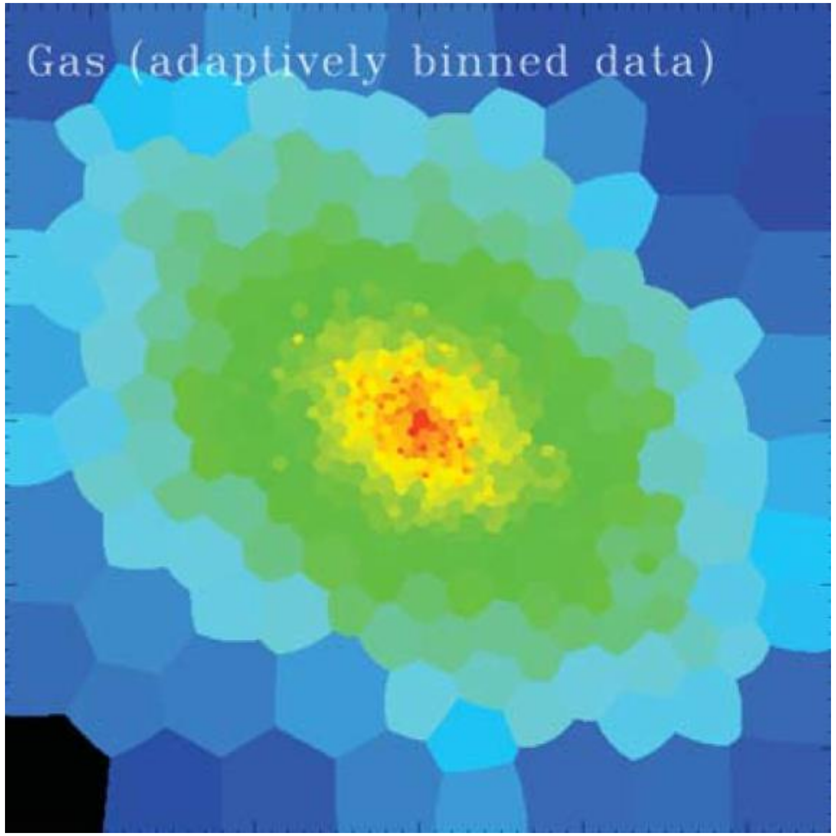


Adaptive binning (aka quadtree)



- Sanders & Fabian (2001)
- Bin brightest pixels first
- Double bin size until fractional error on counts (or count ratio) is reached
- Negative: ugly, big steps in bin size
- I probably wouldn't use this any more

Voronoi tessellation adaptive binning

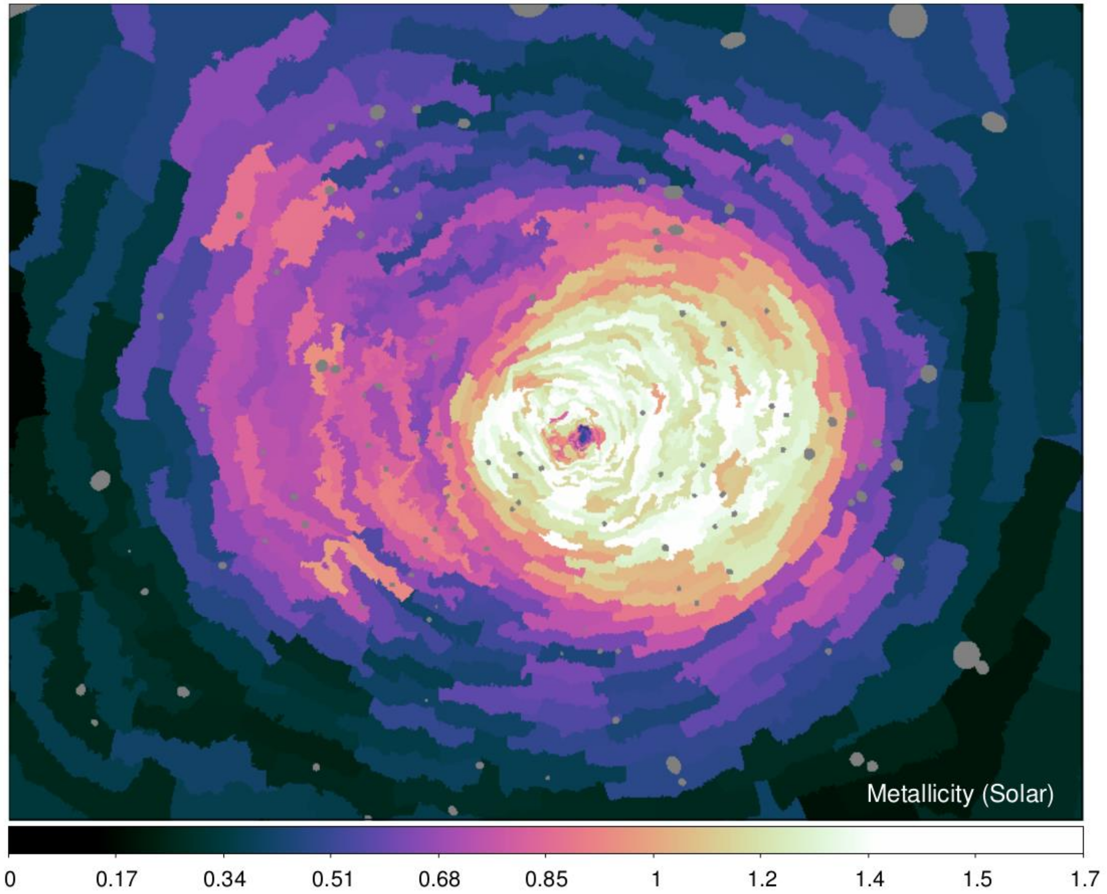


- Diehl & Statler (2006)

1. "Accrete" bins from brightest remaining region to be above a S/N threshold
2. Calculate centroids of bins
3. Perform Voronoi tessellation on centroids
4. Repeat 2.

- Positive: pretty unbiased choice of bins around a S/N value
- Positive: spatially-compact bins
- Negative: non-optimal shape

Contour binning



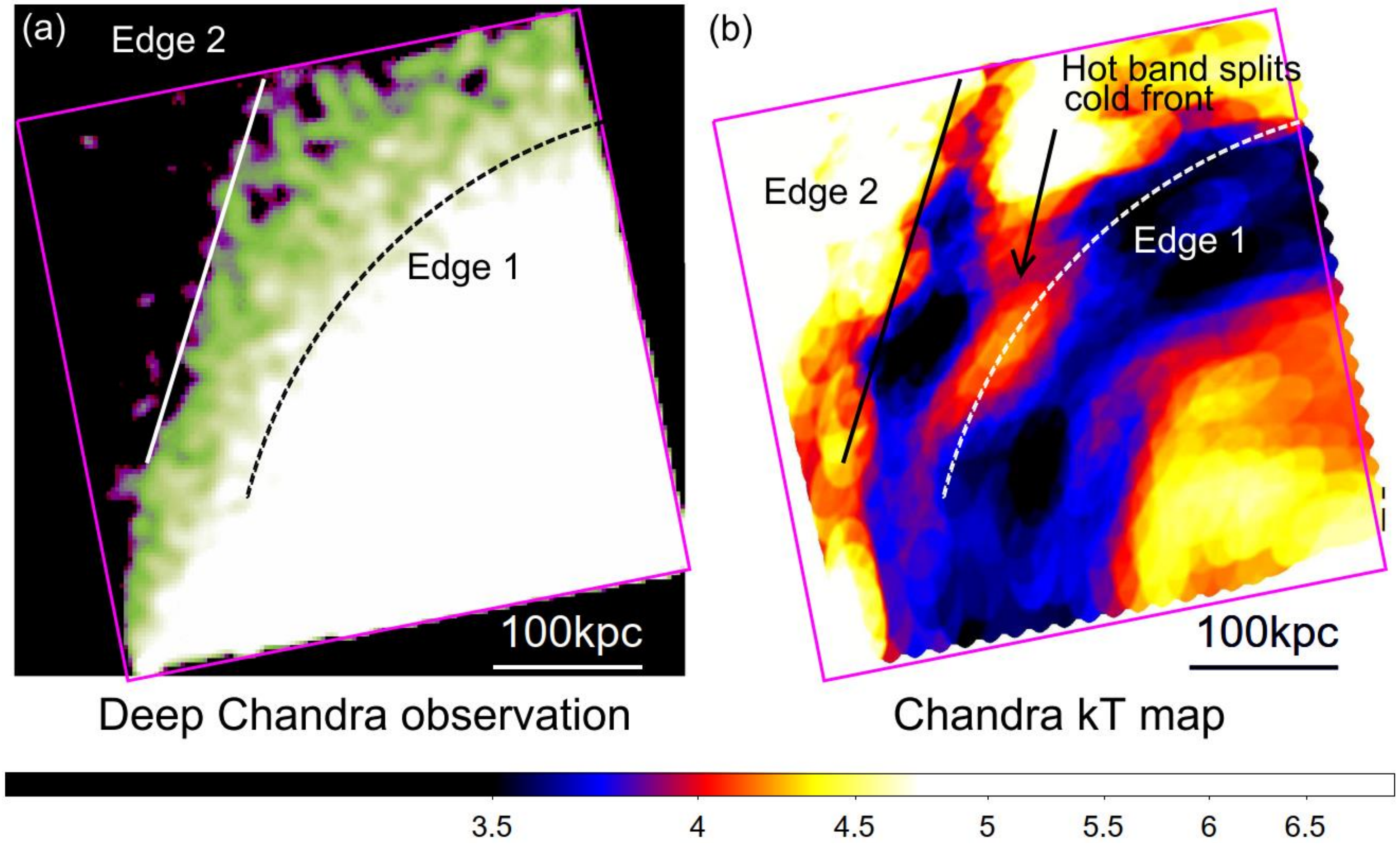
- Sanders (2006) – assumes spectral properties follow image

- Take adaptively smoothed image
- Grow bins along surface brightness contours in map until S/N threshold reached
- Geometric constraints factor to stop elongation of bins

- Positive: Great if spectral properties follow image, and can look nice
- Negative: Possible bias in assuming this

Non-independent binning

- Overlapping circles or ellipses, with size chosen to give S/N ratio, e.g.
  - O’Sullivan et al. (2014)
  - Walker et al. (2018)
- Smoother maps
- More statistically difficult to interpret fluctuations

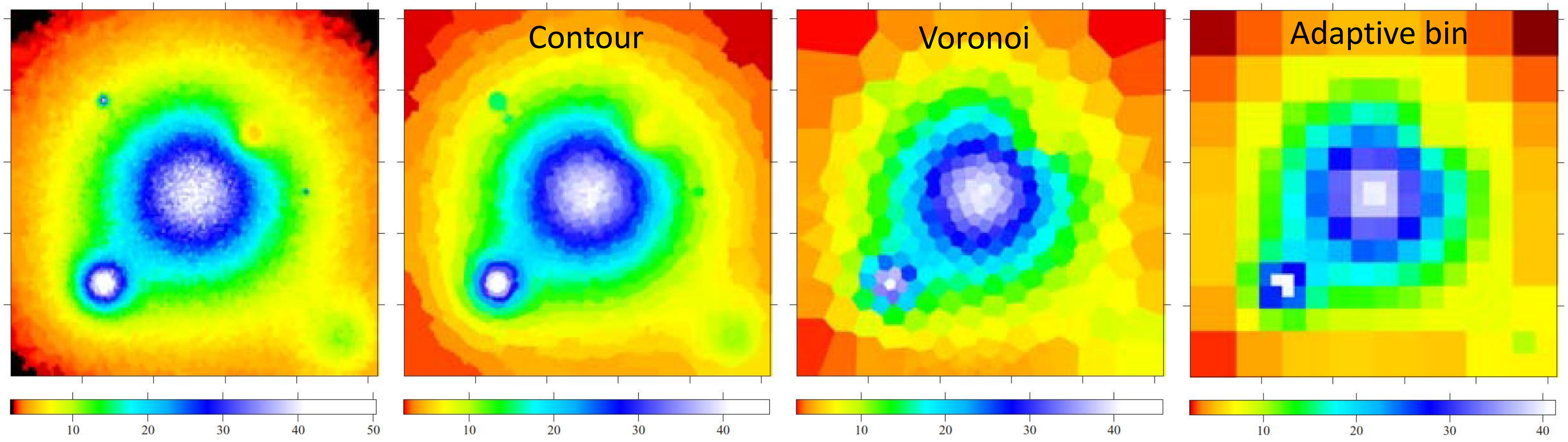


Deep Chandra observation

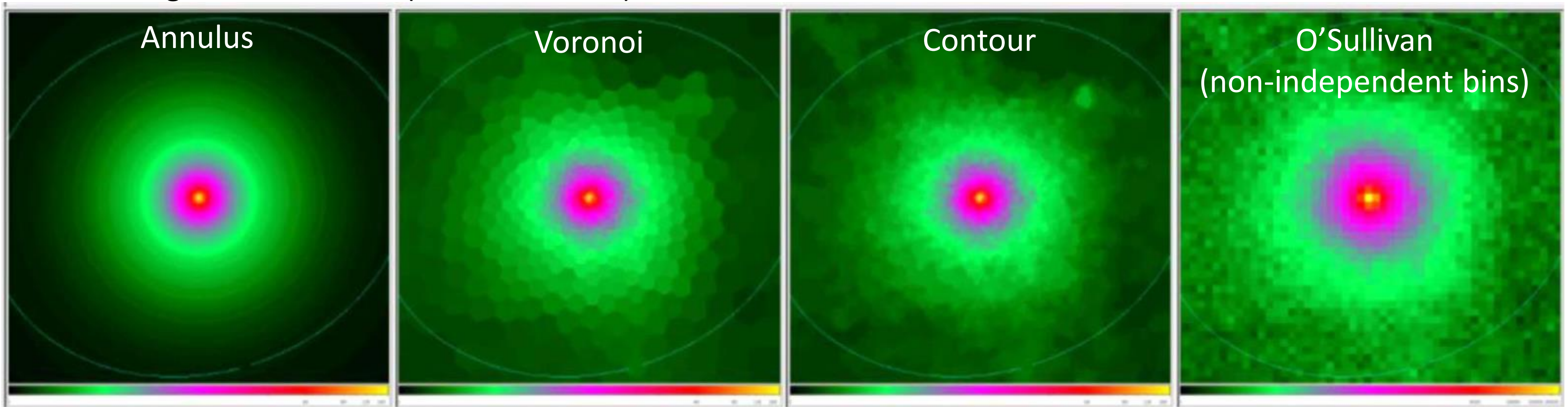
Chandra kT map

Comparison

S/N=100 threshold on model simulated data (Sanders 2006)

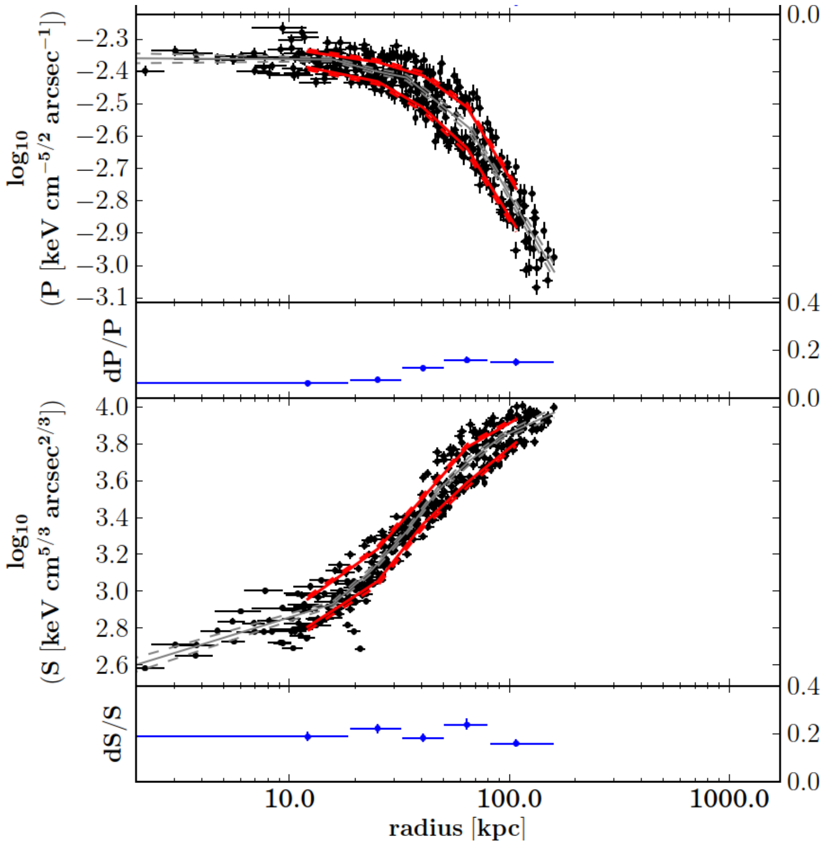


Binned images of NGC 4649 (Kim et al. 2019)

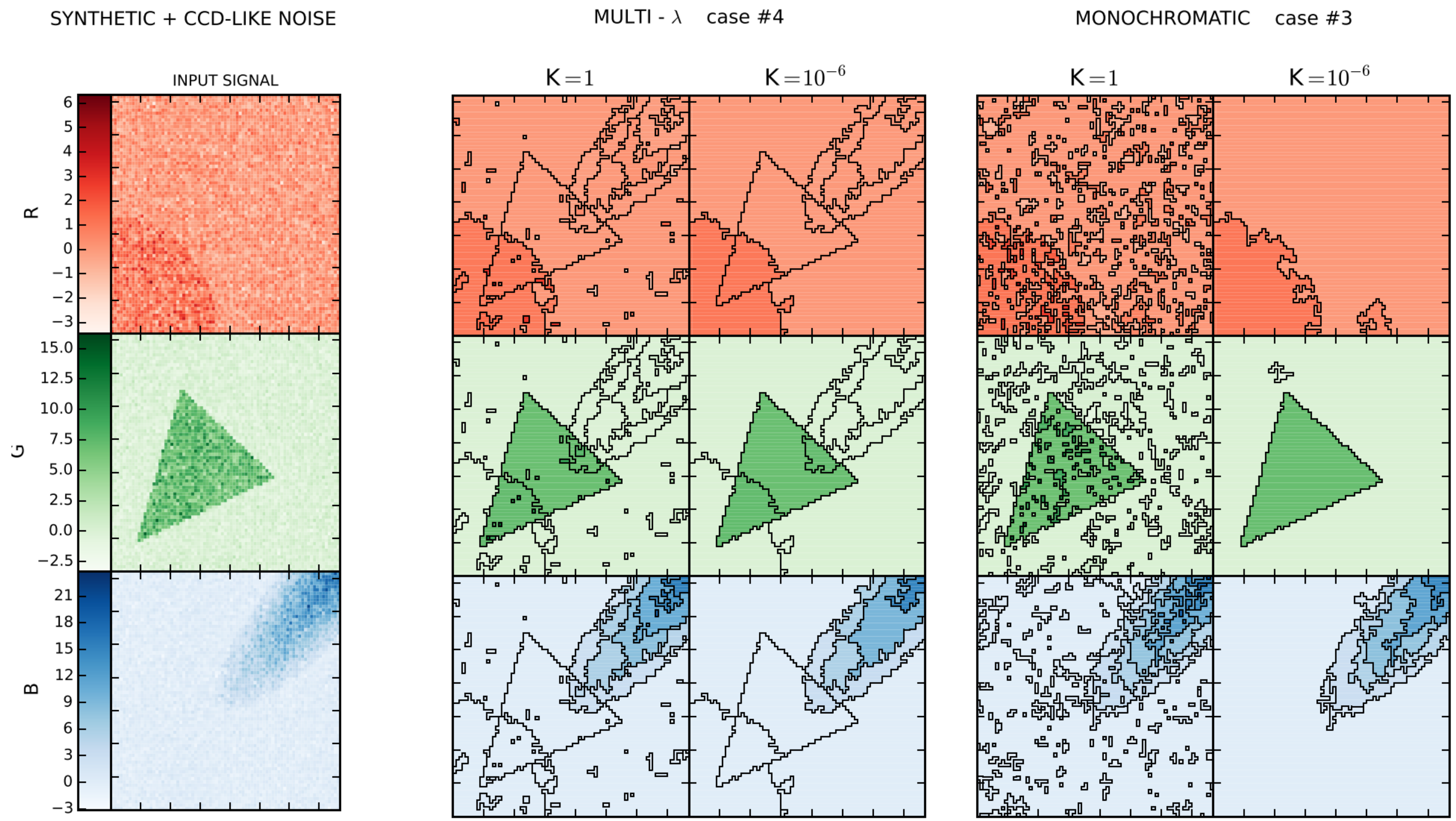


Mapping difficulties

- Not obvious how to choose bin size for optimal mapping
- Statistical significance of physical parameters hard to see in maps
  - Can use radial profiles to help (e.g. Hofmann et al. 2016)



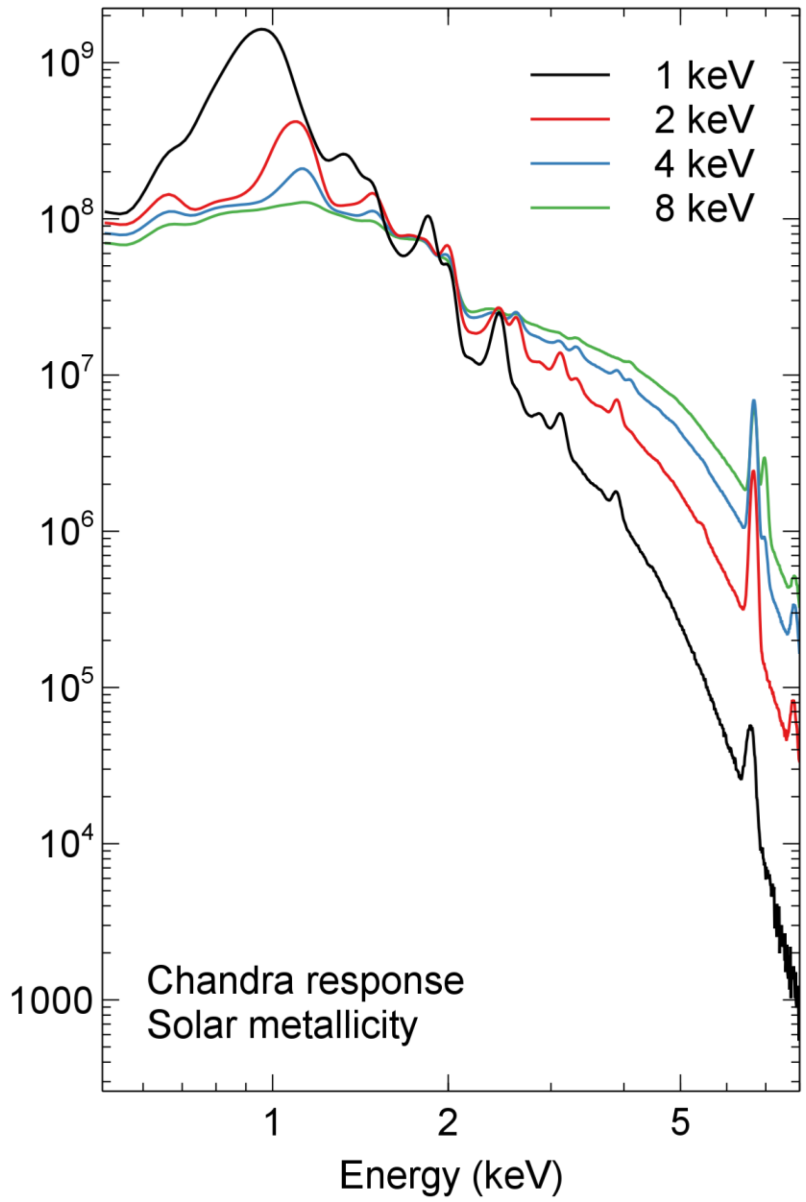
An alternative



- BATMAN: Bayesian Technique for for Multi-Image Analysis (Casado+17)
- Merge regions which are consistent with carrying same region
- Not aware of any X-ray analyses using this
- Issue: huge possible parameter space for regions, so need heuristics

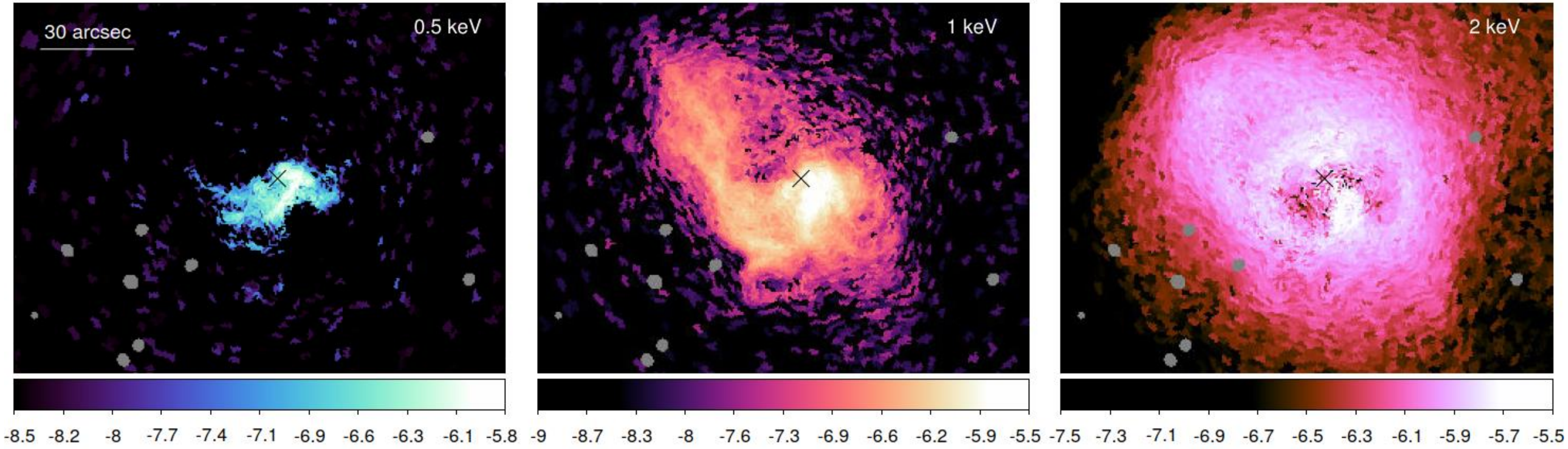
Models

- For galaxy clusters, usually thermal, collisionally-ionized plasma (APEC or MEKAL/SPEX), with Galactic absorption is assumed
  - Parameters: temperature, metallicities (assume Solar or not), redshift, emission measure (can be used to derive density, given geometry)
  - Possible two-component fits in cool cores
- More complex in SN remnants and galaxies
  - Stronger velocities
  - Non-ionization equilibrium
  - Non-thermal components (e.g. binaries in galaxies)

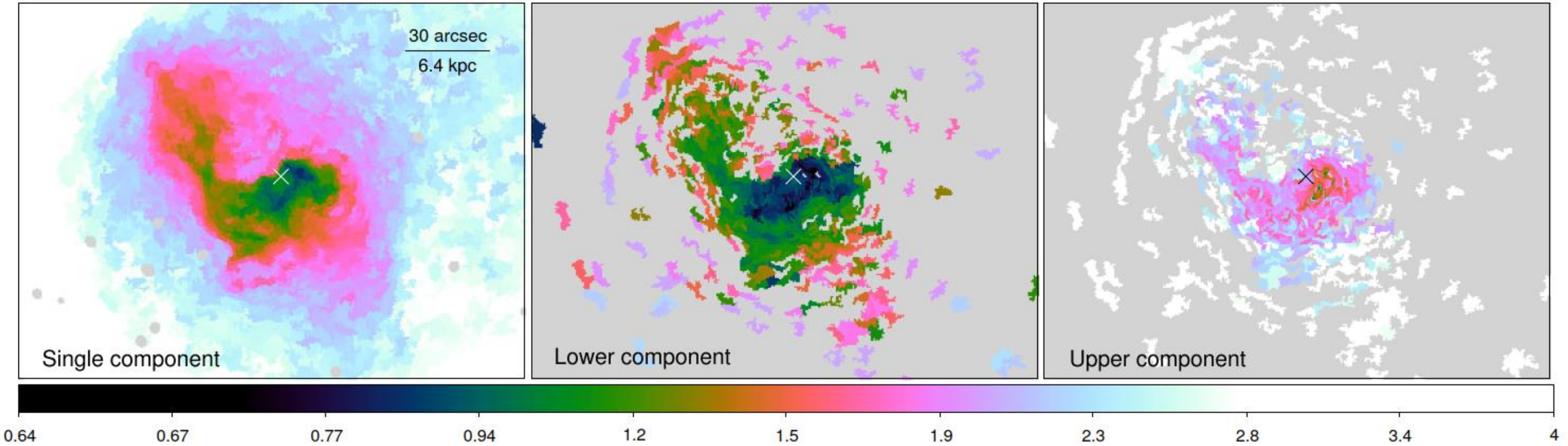


More complex models: Centaurus

Multi-component model with fixed temperatures, showing normalisation of each component (Sanders+17)

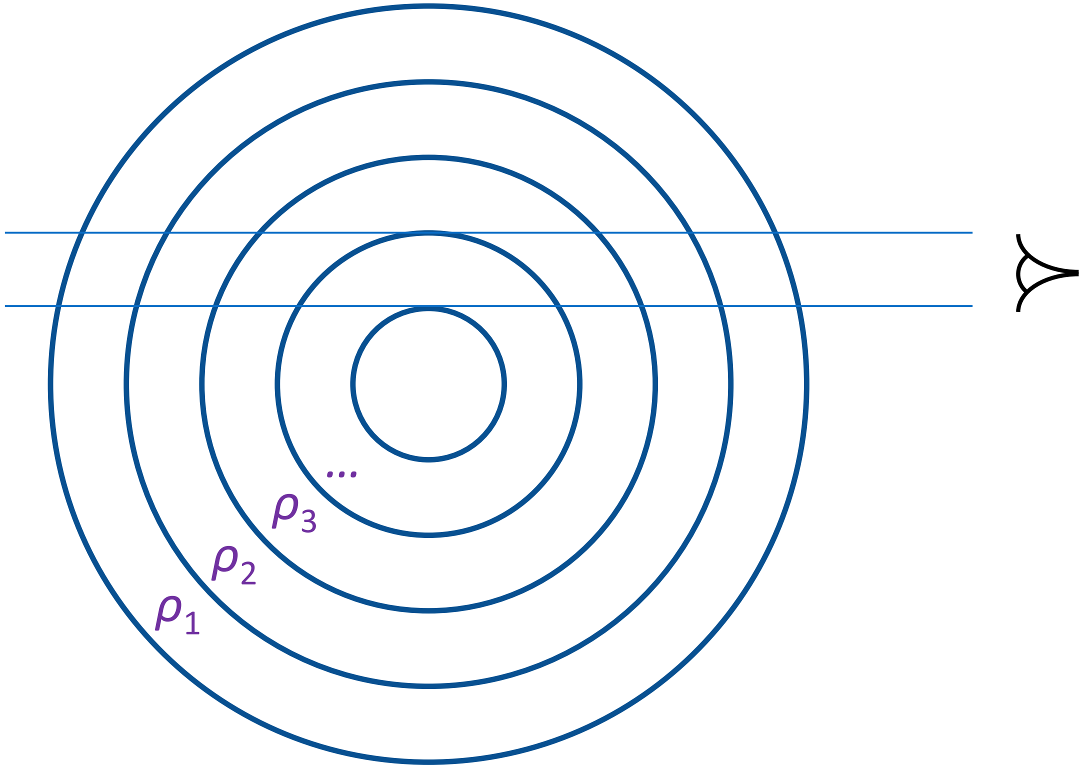


Model with a range of temperatures, using simulations to decide statistical significance



Projection

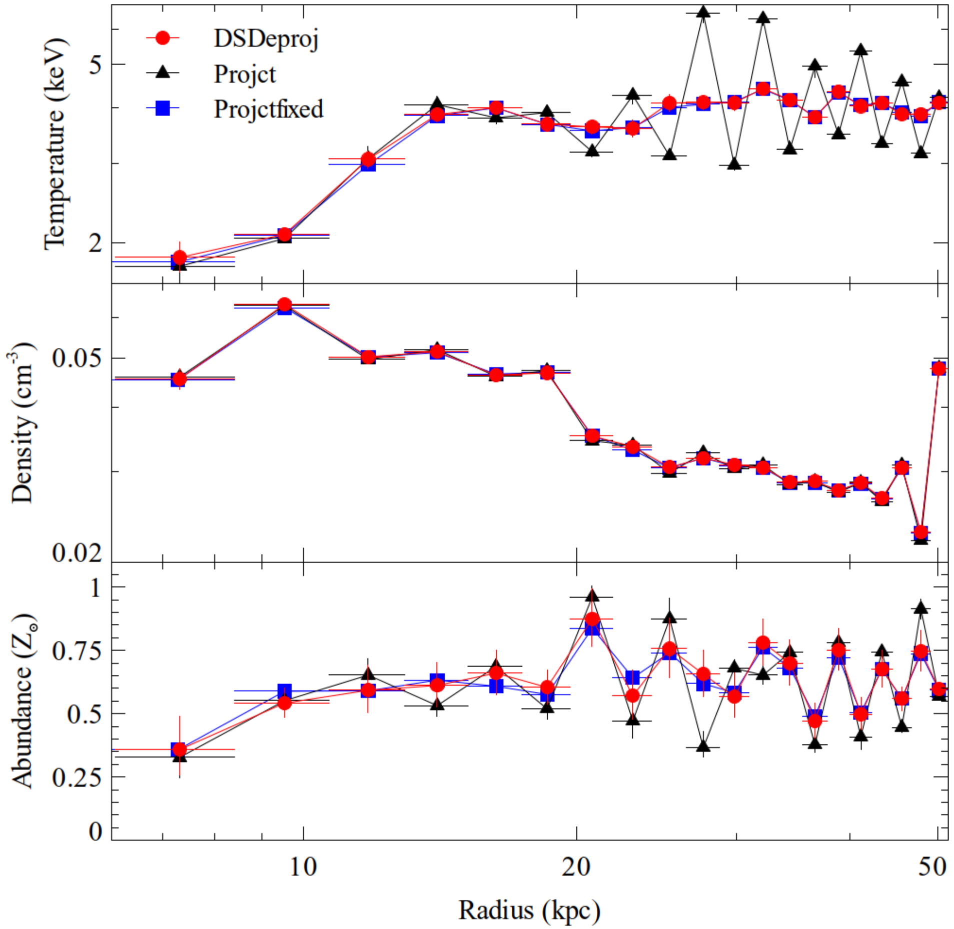
- The quantities plotted in maps are obtained from spectra projected along the line of sight (emission-weighted)
- How important projection is depends on the line-of-sight structure/profile
- Usually in X-rays (for clusters) plasma is optically thin (except in resonance lines)
- Intrinsic 3D variations are larger than seen in 2D
- Would like radial profiles, examining spectra in 2D annuli / annular ellipses
  - When examining radial profiles, obtain “projected quantities”
  - Would like 3D profiles of the intrinsic values



Decoding projection

- Modelling with assumptions (e.g. spherical) to get 3D intrinsic profile
  - Correcting projected quantities (e.g. Ettori+02) – would be hard to do properly
  - PROJCT in Xspec – forward modelling spectra from annuli with 3D shells – sometimes problems with instabilities in fits (e.g. oscillations in parameters) – see Russell+08
  - DSDeproj – deproject spectra (not so nice statistically!), but avoids instabilities (Sanders+07)

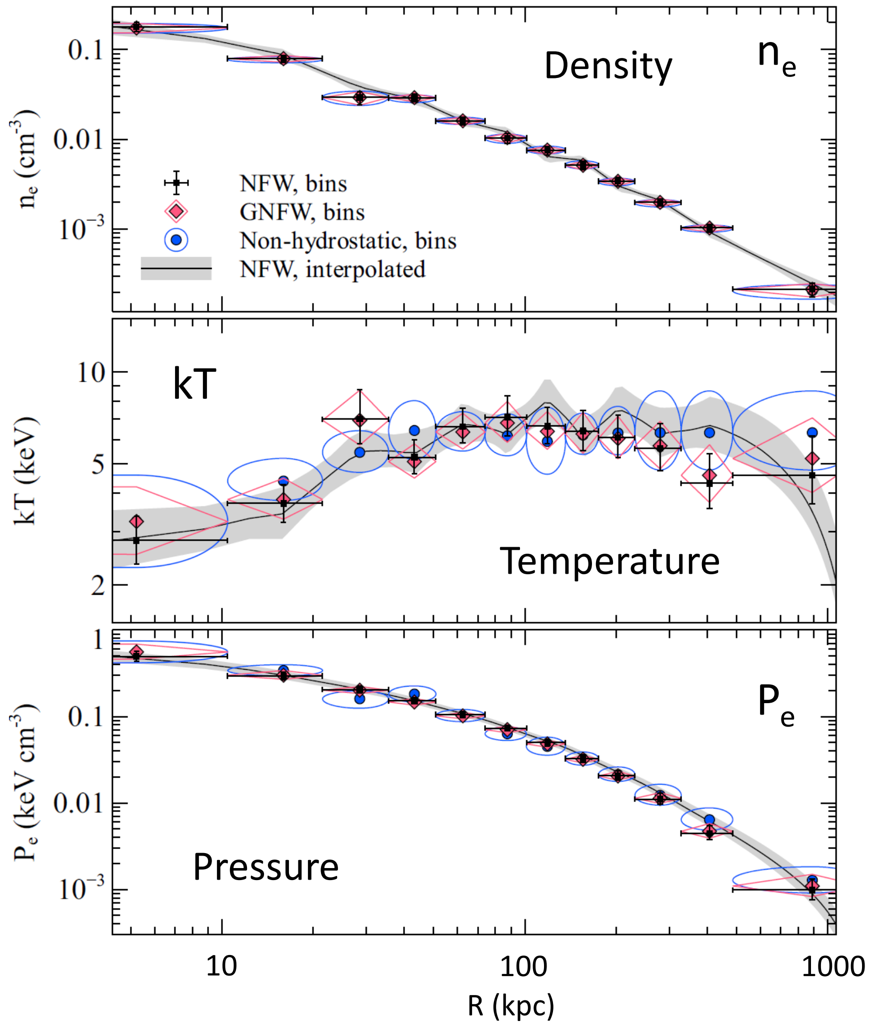
Russell+08



Decoding projection

- Forward fitting of mass + temperature to spectra extracted from shells (Mahdavi+08, Nulsen+10)
- MBProj2 – forward modelling of surface brightness profiles in multiple energy bands (Sanders+18), either with or without the assumption of hydrostatic equilibrium. Uses MCMC, producing uncertainties on output profiles.
- Bayes-X – forward-model events from 3D model (Olamaie+18), using multinest

MBProj2

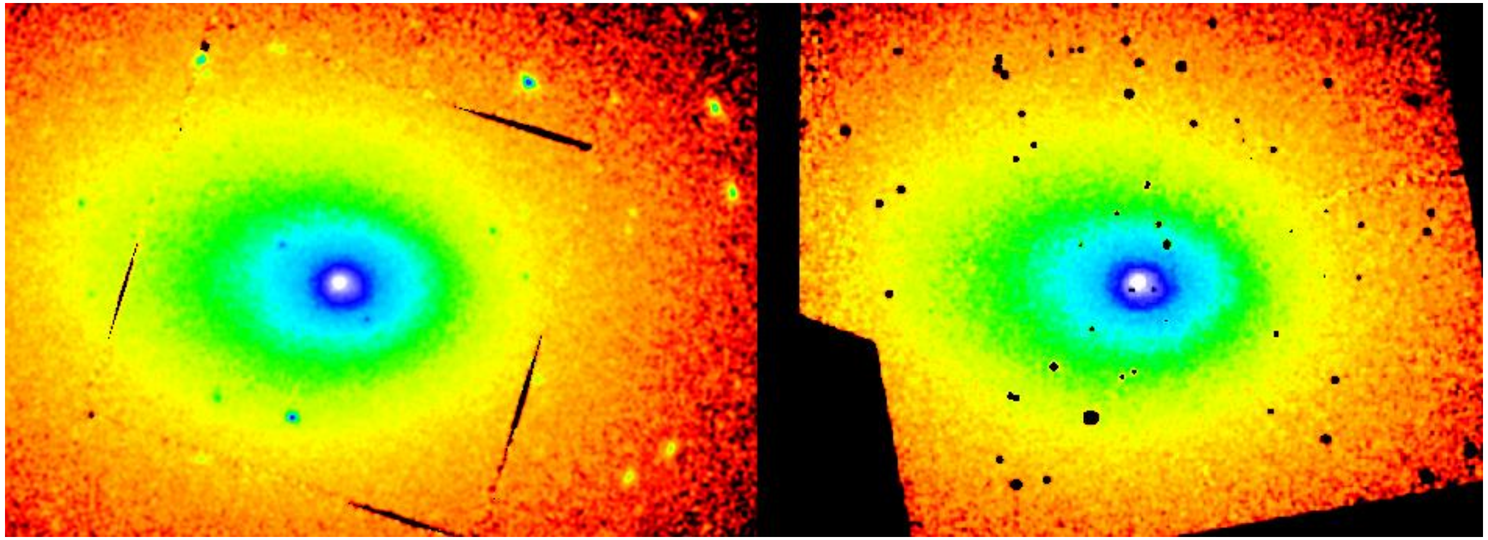


Instrumental and modelling difficulties

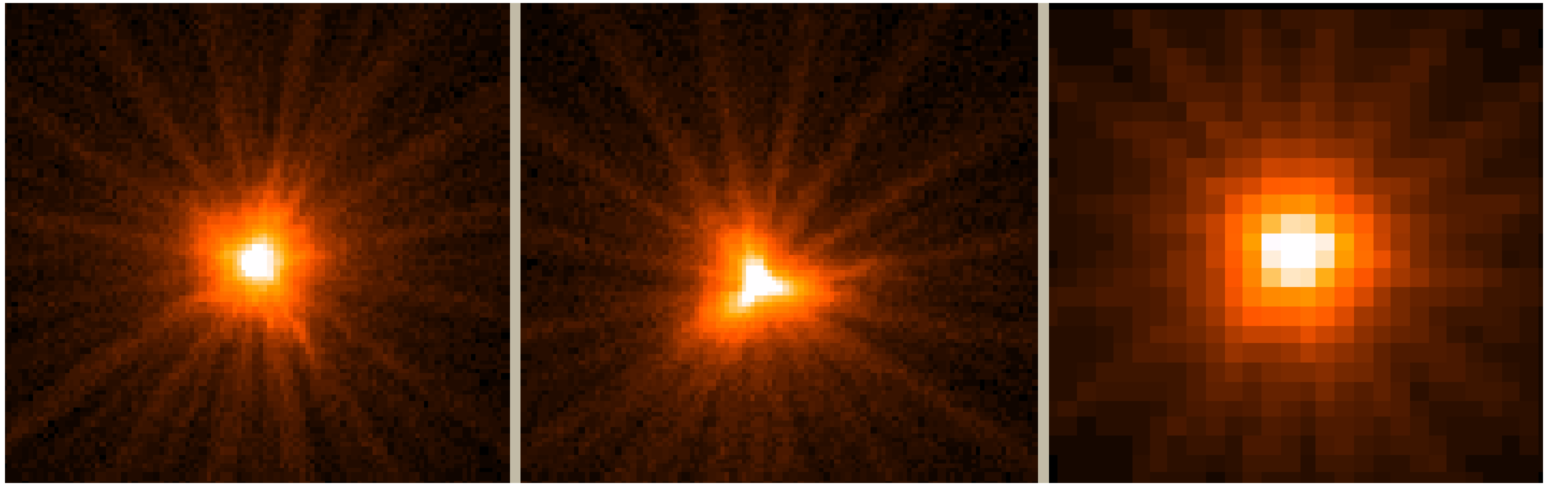
- Point sources
- PSF
- Vignetting / response
- Multiple datasets
- Background
- Out-of-time events

Point sources

- Usually masked out during spatial analysis (take care of PSF!)
  - Or could be modelled in analysis (e.g. Bayes-X)
- Point sources can be difficult to detect and remove in bright extended sources
  - Structures in extended sources can be confused as point sources by source detection codes
  - Sometimes need to be fixed by hand



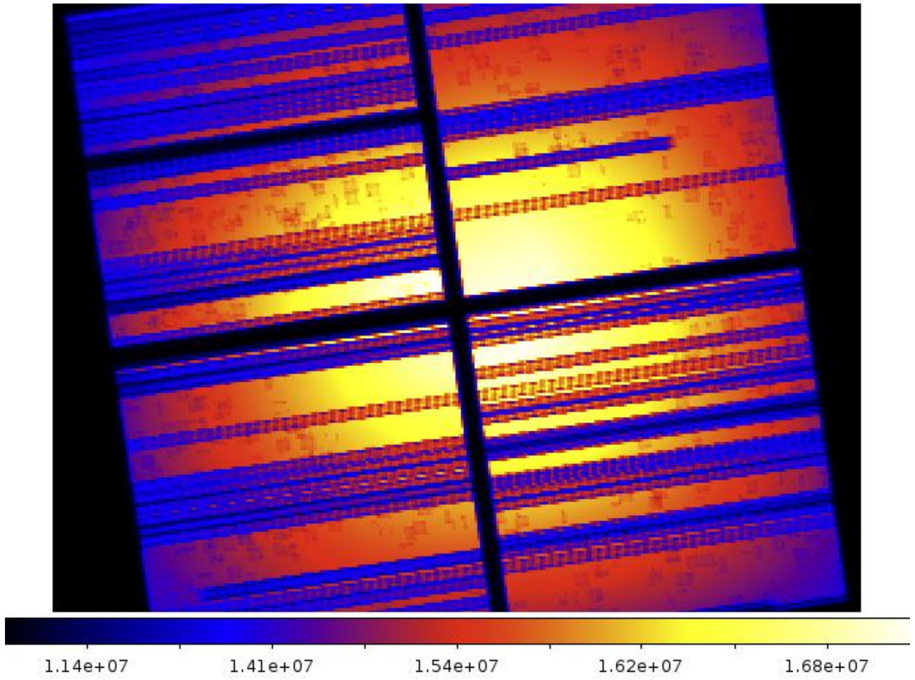
PSF



- Varies as a function of energy and position
- If region size >> PSF, then not so important
- Difficult to account for in mapping
  - See NuStar results, e.g. Wik+14
  - Difficult to model mixing between different bins – potential parameter instabilities
- In 2D profiles, e.g. MBProj2, can account for PSF by using some sort of mixing model when calculating projected spectra

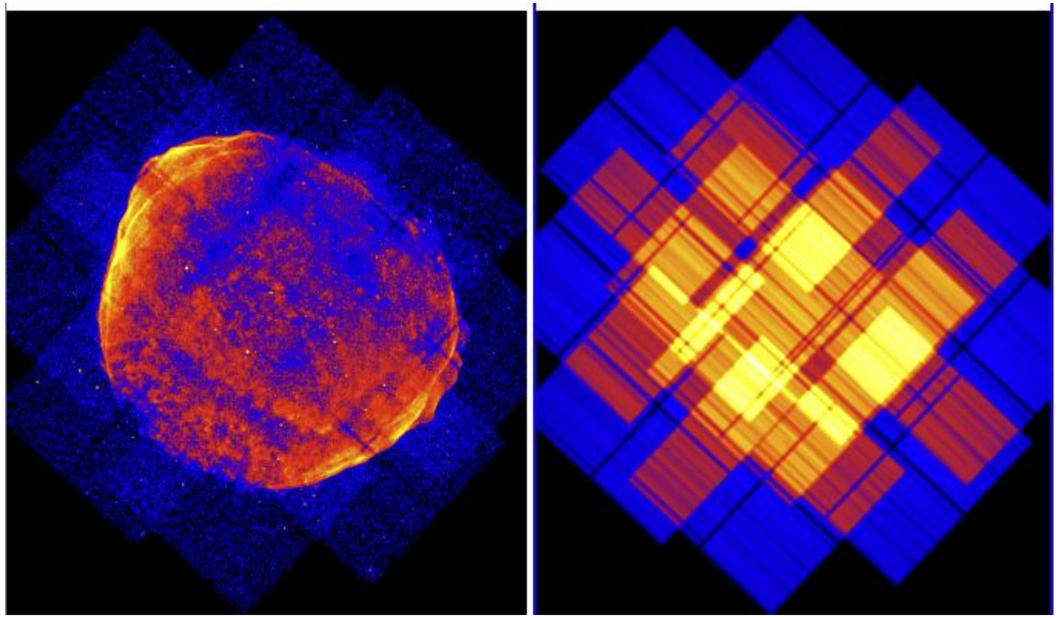
Vignetting and response

- ARF and RMF varies over detector
- Sometimes simplified to single RMF or single ARF
- Possible issues to do with
  - Weighting of regions of the detector when calculating ARF/RMF – people often use distribution of counts when weighting spatial regions, but not completely statistically proper
  - Chip gaps and detector edges – are these properly included in ARF?



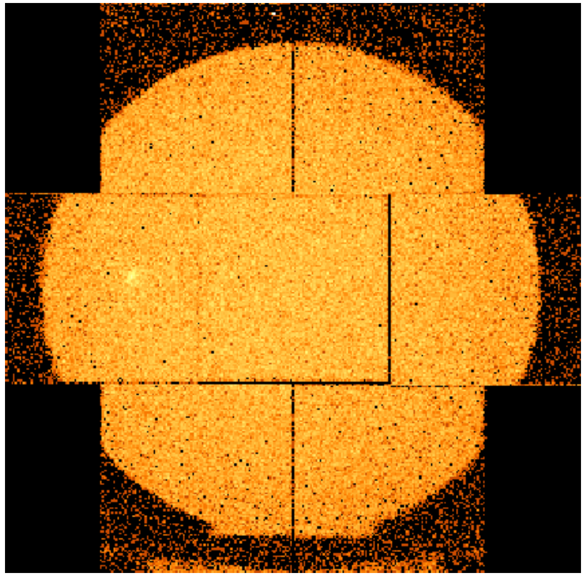
Multiple datasets

- Possibilities
  - Simultaneous fit of spectra, allowing varying normalizations between spectra (differences in vignetting, chip gaps, detector edges)
  - Add spectra together and weight responses, ARFs



- Adding is a lot easier, but less statistically nice – be very careful!
  - Don't add data if the detectors have different performance!

Background



- Complex and difficult topic (e.g. Molendi 2017)
- Various components, e.g.
  - Unresolved point sources
  - Soft Galactic foreground
  - Quiescent particle background
  - Soft protons which can flare
- Need appropriate model for spectra of background components over detector, or a background event file, with low systematic uncertainties
- How important this is depends on the faintness of region to analyse (vital in cluster outskirts)
- Far easier if you have a source-free region in your observations
  - Can use to model or to check background modelling
  - Corners of XMM EPIC-MOS cameras can be used to normalise background

Background 2

- For XMM EPIC-MOS, there is an ESAS package for modelling background, though can be inflexible
- New XMM EPIC task for quiescent background creation: eqvpb

- Chandra has blank-sky background event files if background is less critical
- Closed-filter particle background event files very helpful
- May need to optimize energy band to minimize background

Out-of-time events (readout streak)

- Event arrives during readout – position is wrong
- Particularly important for certain detector modes and instruments
- Leads to a streak along the readout direction
- More of a problem if you have large contrast in source (e.g. cool core cluster)

- Usually treated as a synthetic background in the analysis
- Tools to create OoT event files from input event files, by randomizing along readout direction