Tools for the analysis of extended X-ray sources

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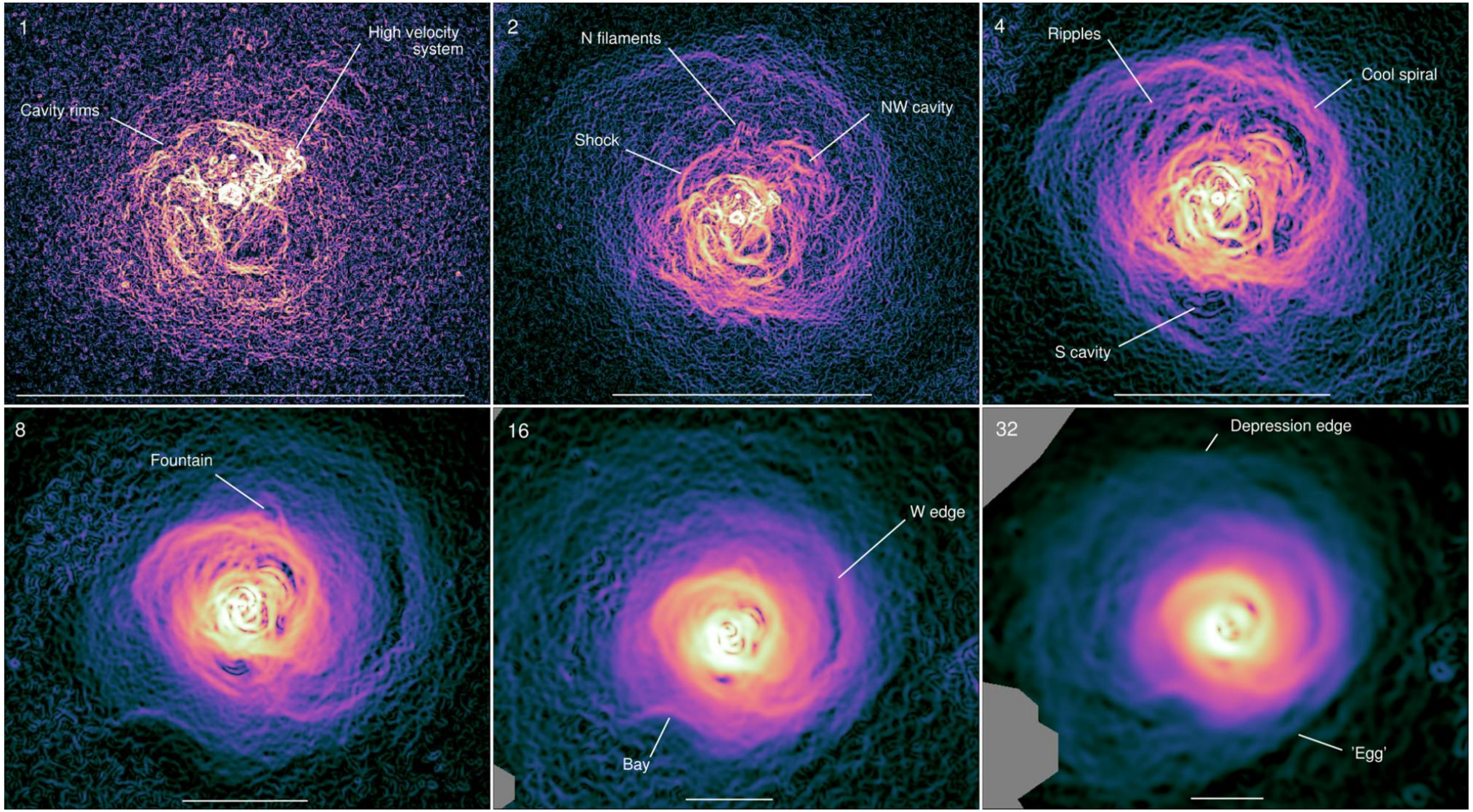
Contents

- X-ray image and edge detection
  - Gaussian gradient magnitude
  - Adaptive gaussian gradient magnitude
- Modelling extended sources
  - Contour binning
  - Ellipse mapping
  - MBProj2/MBProj2D

Looking for structures by measuring gradients: GGM

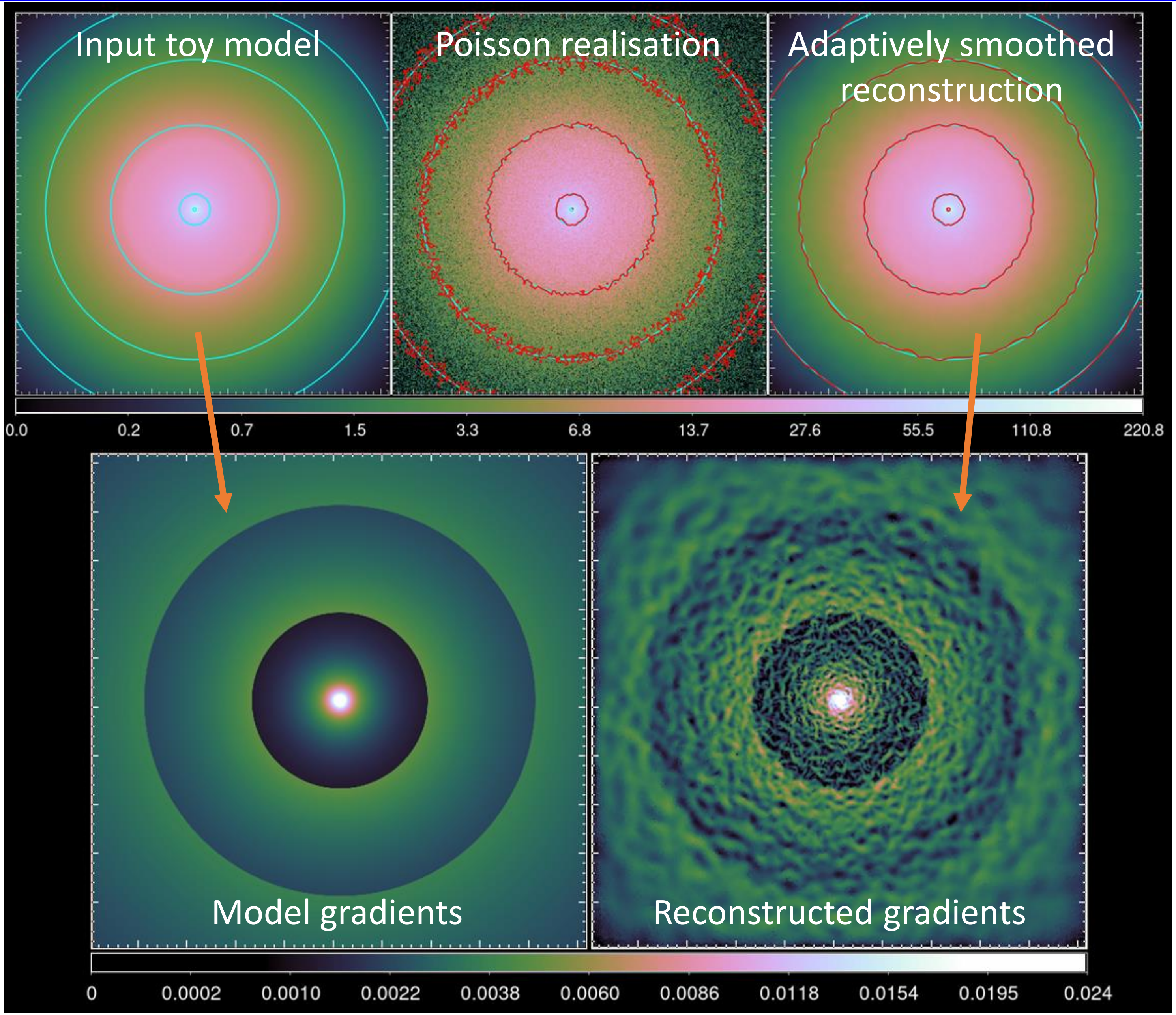
- Sanders et al. (2016) introduced the *Gaussian Gradient Magnitude* (GGM) filter in X-ray astronomy – look for gradients and edges in images
- Physical changes give gradients and edges
- GGM measures gradient on one size scale (σ)
- Disadvantage: noise larger in the outskirts, where are fewer counts



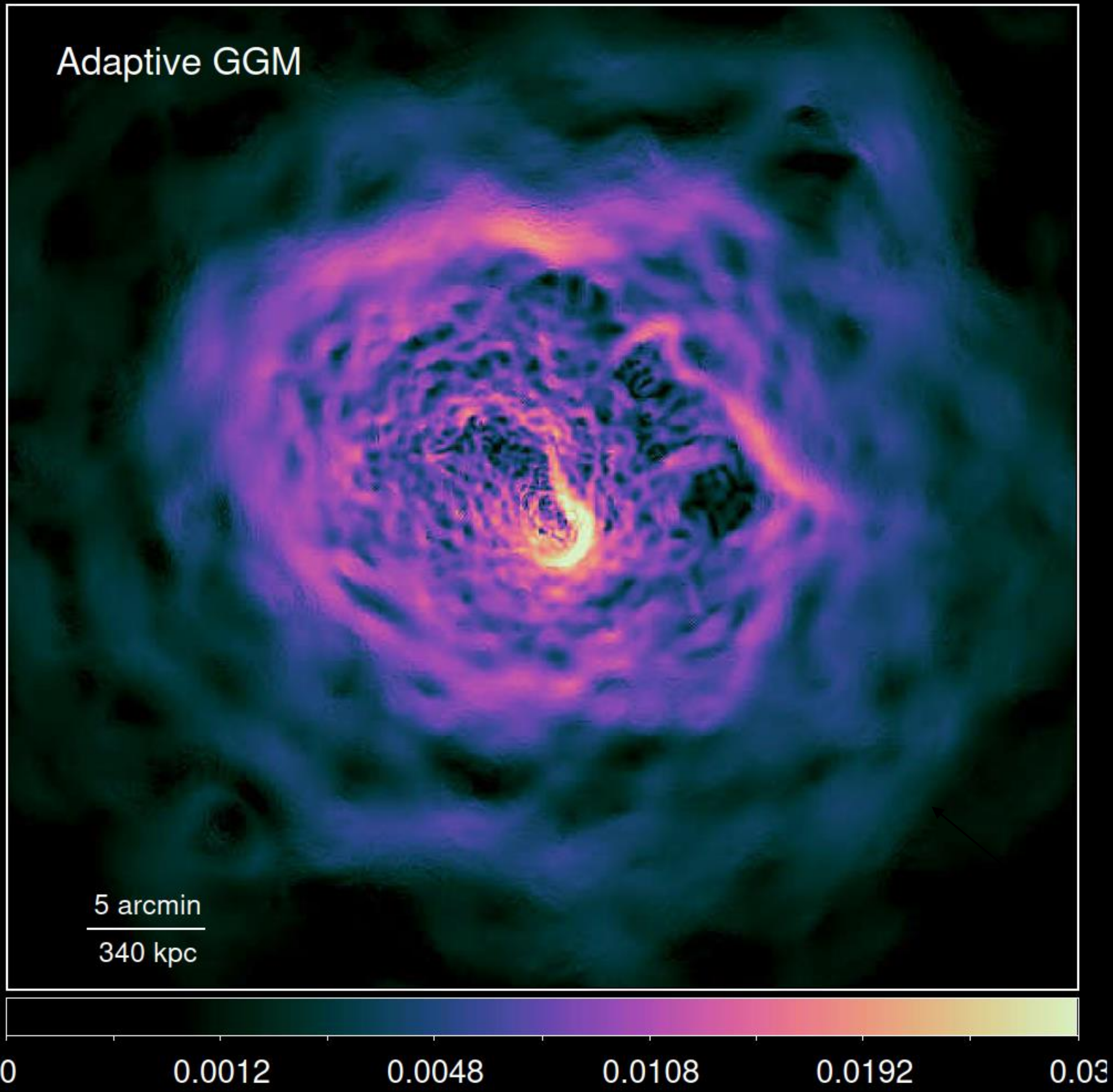
Perseus Chandra cluster images, with GGM filtering on different scales

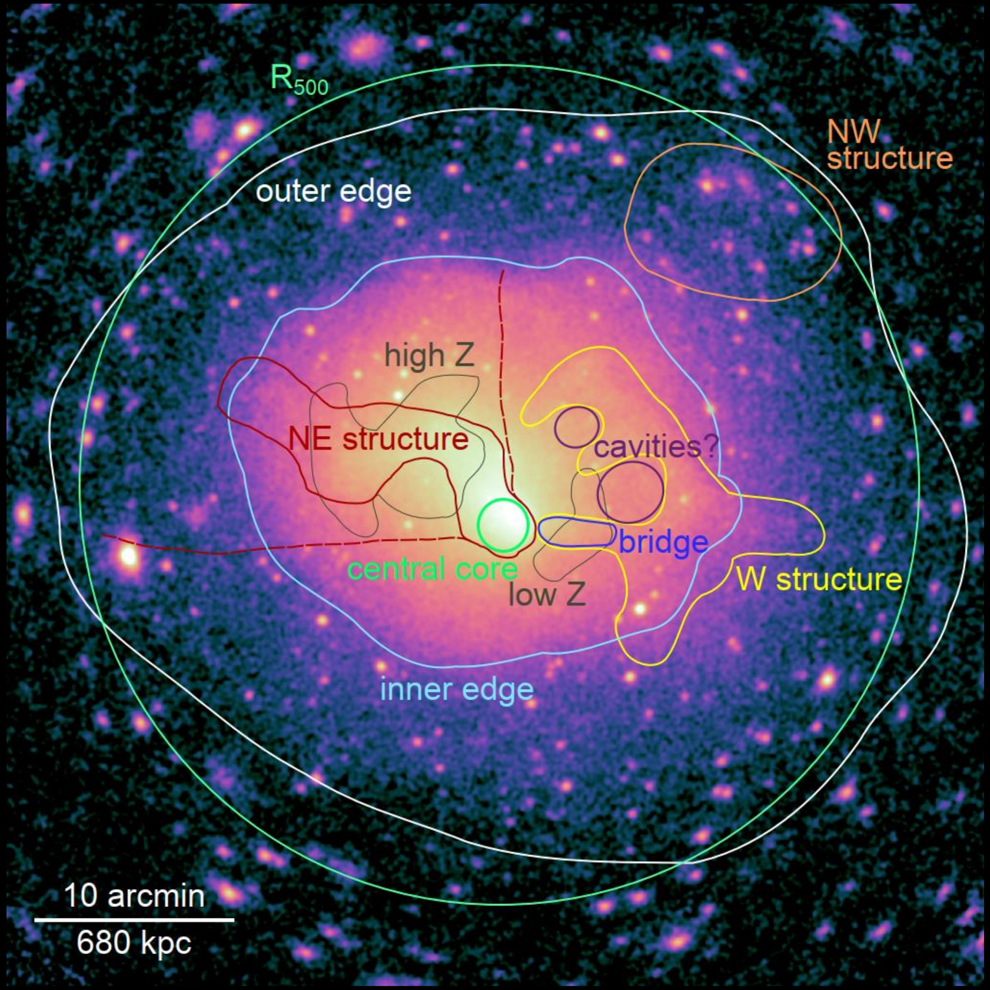
Measuring gradients: adaptive GGM

- Relatively simple
- Apply adaptive smoothing
  - Around each pixel, measure radius containing a given S/N ratio (or number of counts)
  - Smooth image (or exposure corrected version) by Gaussian where σ is this radius, as a function of position
- Optional: take log
- Measure gradient of above image
- Implementation available: https://github.com/jeremysanders/ggm



Sanders et al. (2021)





A3266 eROSITA observation
(note: code can mask and smooth over point sources)

Sanders et al. (2021)

Approaches to modelling extended objects

- Binning
  - Advantages: independent regions in maps and spectra
  - Disadvantage: non-optimal use of data
- Smooth map techniques
  - Advantages: look nicer
  - Disadvantages: time consuming to make (if spectral fitting), hard to assess statistical significance, as pixels not independent
- Forward modelling
  - Advantages: Can include PSF, etc. Good for model parameter uncertainties
  - Disadvantages: Can be very slow. Needs a good model.
- Instead of spectral fitting, ratio maps, etc, can be used

Binning methods

- *Adaptive Binning* (Sanders & Fabian 2001) – binning (or subdividing) squares until S/N is reached
- *Centroidal Voronoi Tessellation*. Cappellari & Copin (2003) – method to make Voronoi bins with similar S/N – compact binning
- *Contour Binning*. Sanders (2006) – bins which follow the surface brightness with given S/N – useful if physical properties follow surface brightness

- Can use spectral fitting or flux ratios to get model parameters
- Implicit assumption is similar S/N gives similar uncertainty on quantity
- Publicly-available codes for above

Contour binning algorithm

1. Adaptively smooth X-ray image
2. Find brightest pixel in map and add to bin
3. Add neighbouring pixel with value closest to starting value, satisfying geometric constraints*
4. Repeat to (3) until S/N threshold is reached for bin or no neighbouring pixels
5. Start new bin from next brightest pixel
6. Clean-up phase: move pixels from bins that haven't reached threshold to neighbours

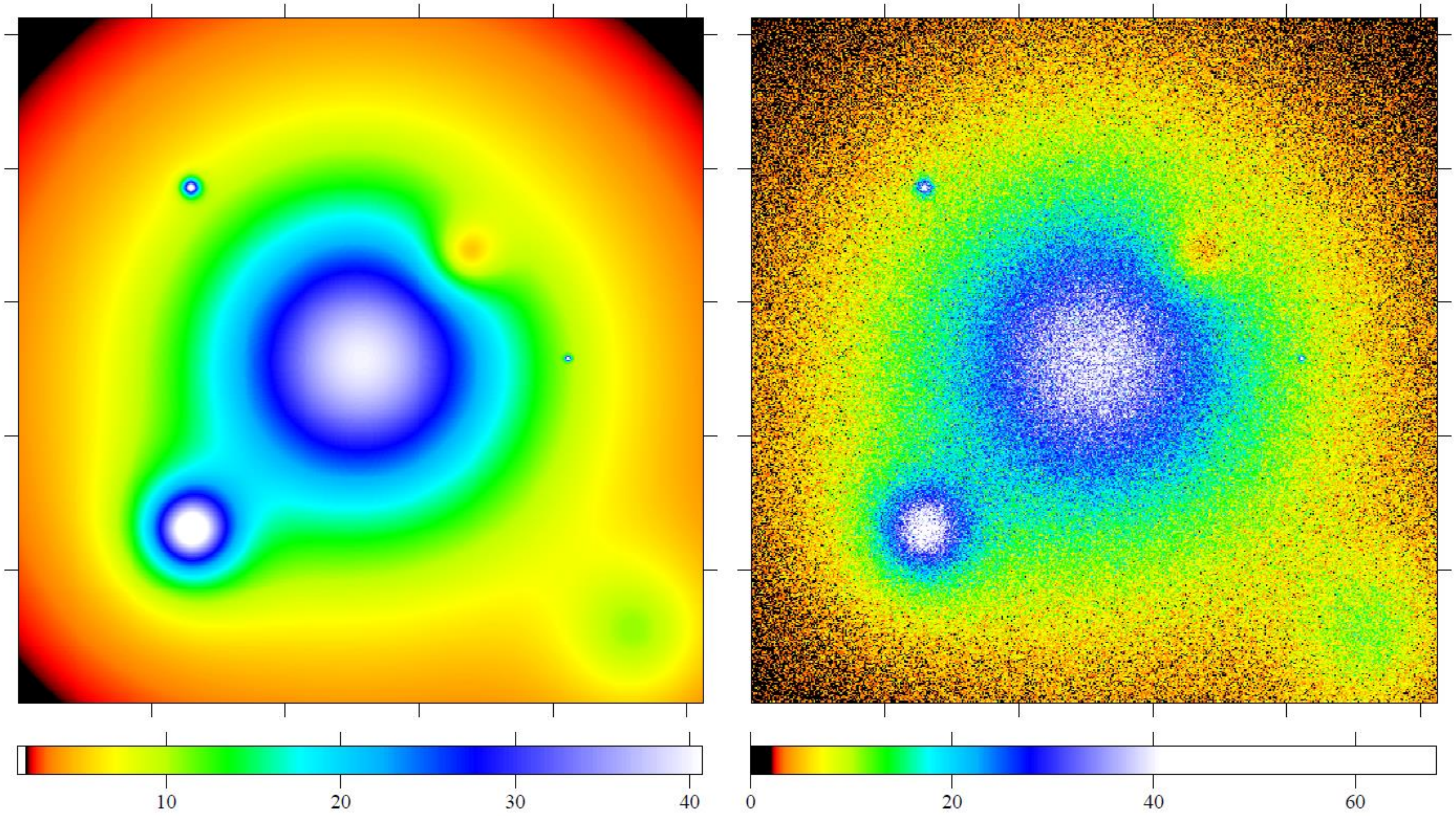
Parameters:
- S/N of bins
- S/N of smoothing (controls regularity, at expense of structure sensitivity)
- Geometric constraint factor (how round bins should be)

* Optional geometric constraint: new pixel should not be more than *C* times radius of circle with same area as current bin

https://github.com/jeremysanders/contbin

Sanders (2006)

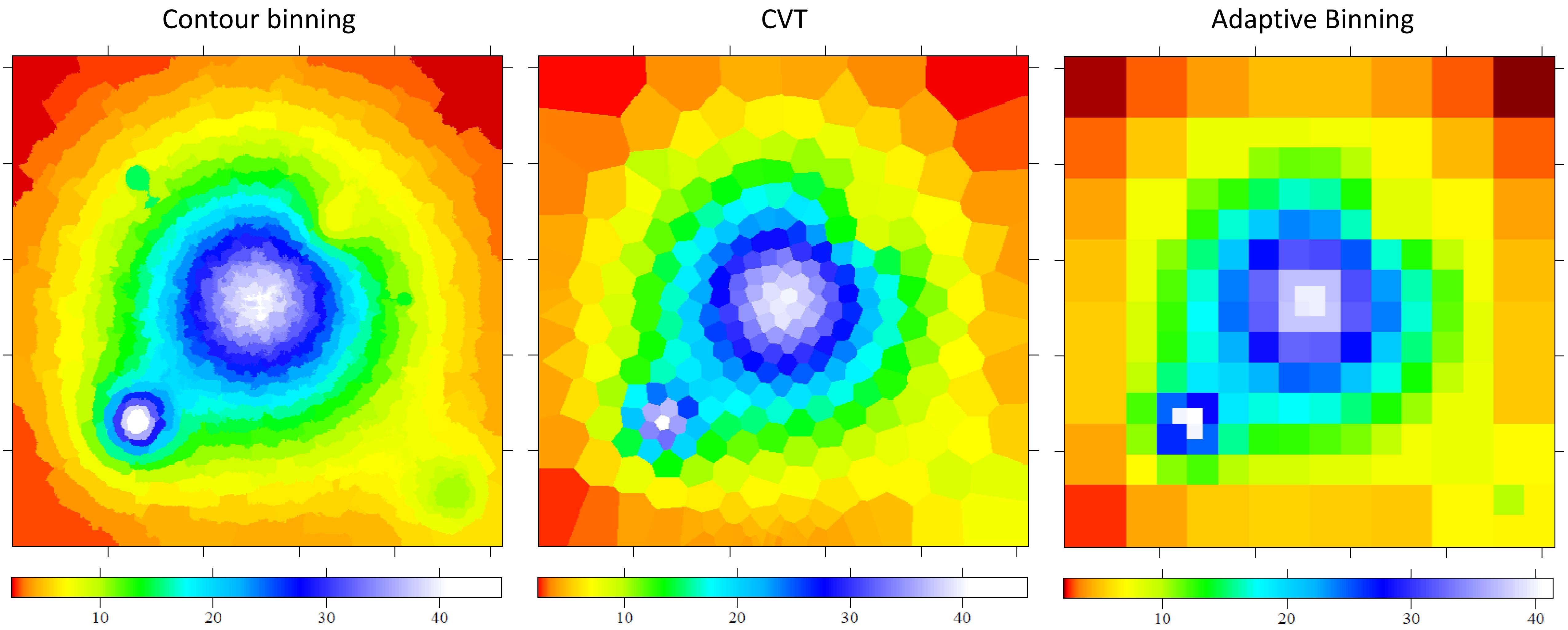
Binning Example - Synthetic



Input model (multiple beta models) and Poisson realisation

Sanders (2006)

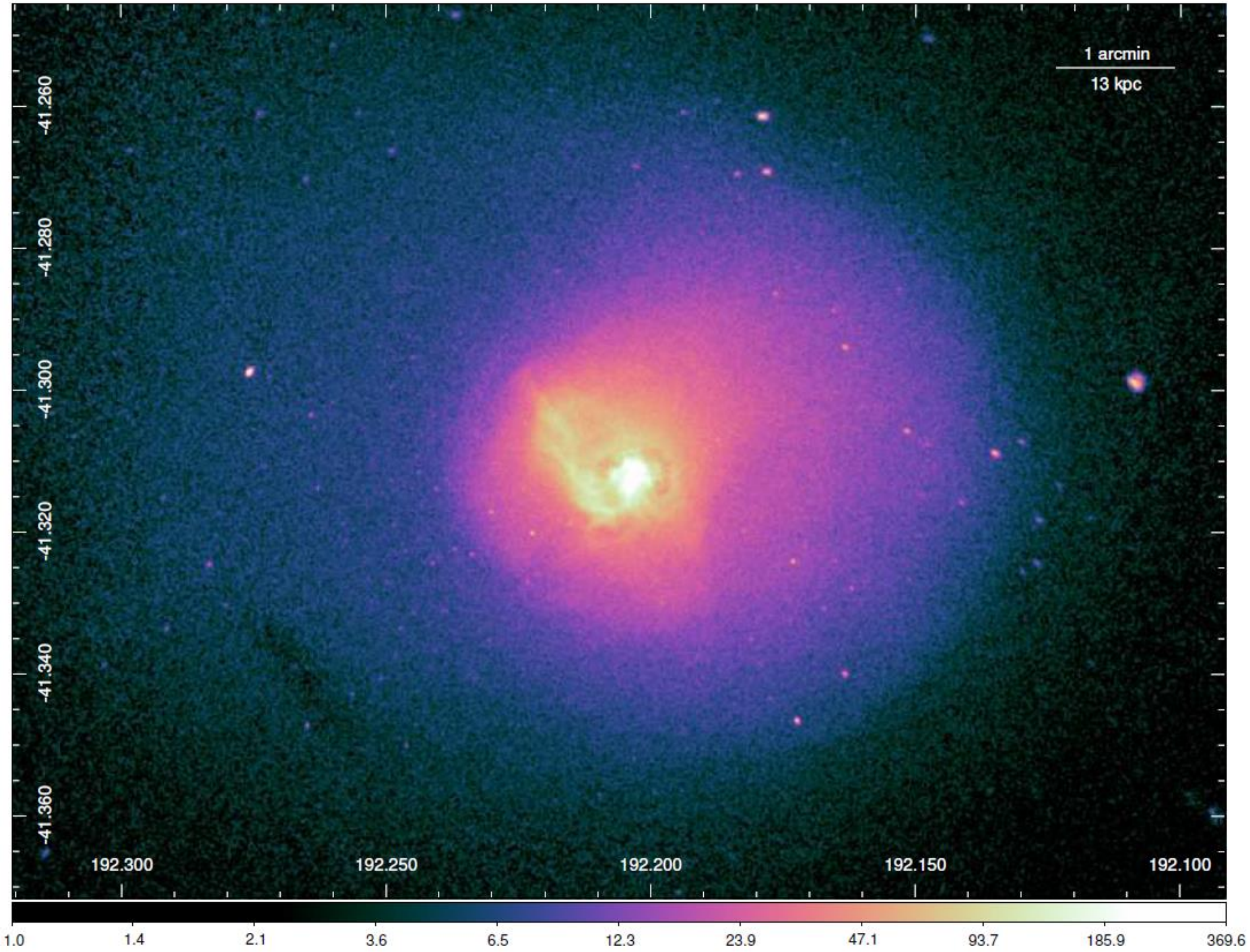
Binning Example - Synthetic



Surface brightness after binning with S/N=100

Sanders (2006)

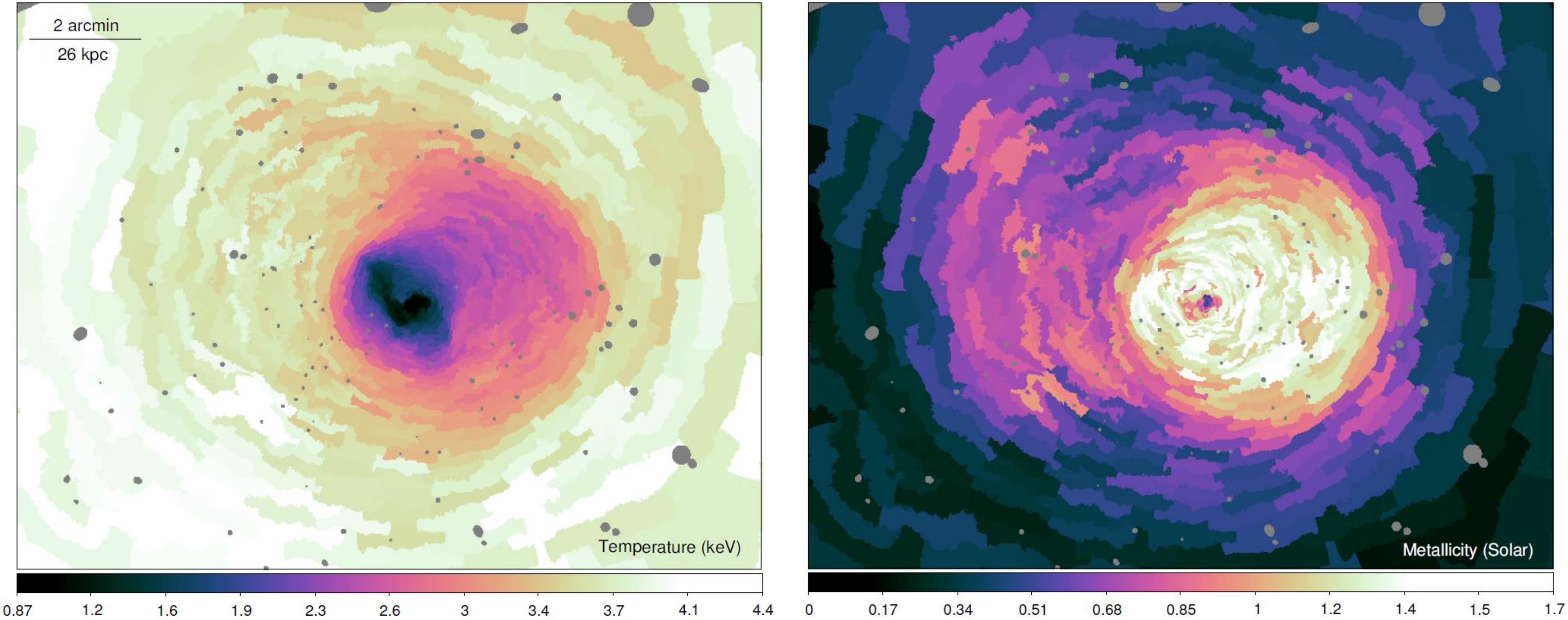
Real world spectral maps – Centaurus cluster



Surface brightness edges are cold fronts (contact discontinuities)

Sanders et al. (2016): Deep Chandra observations of the core of the Centaurus cluster

Real world spectral maps – Centaurus cluster



Sanders et al. (2016): Deep Chandra observations of the core of the Centaurus cluster. Fitting APEC model to spectra extracted from bins.

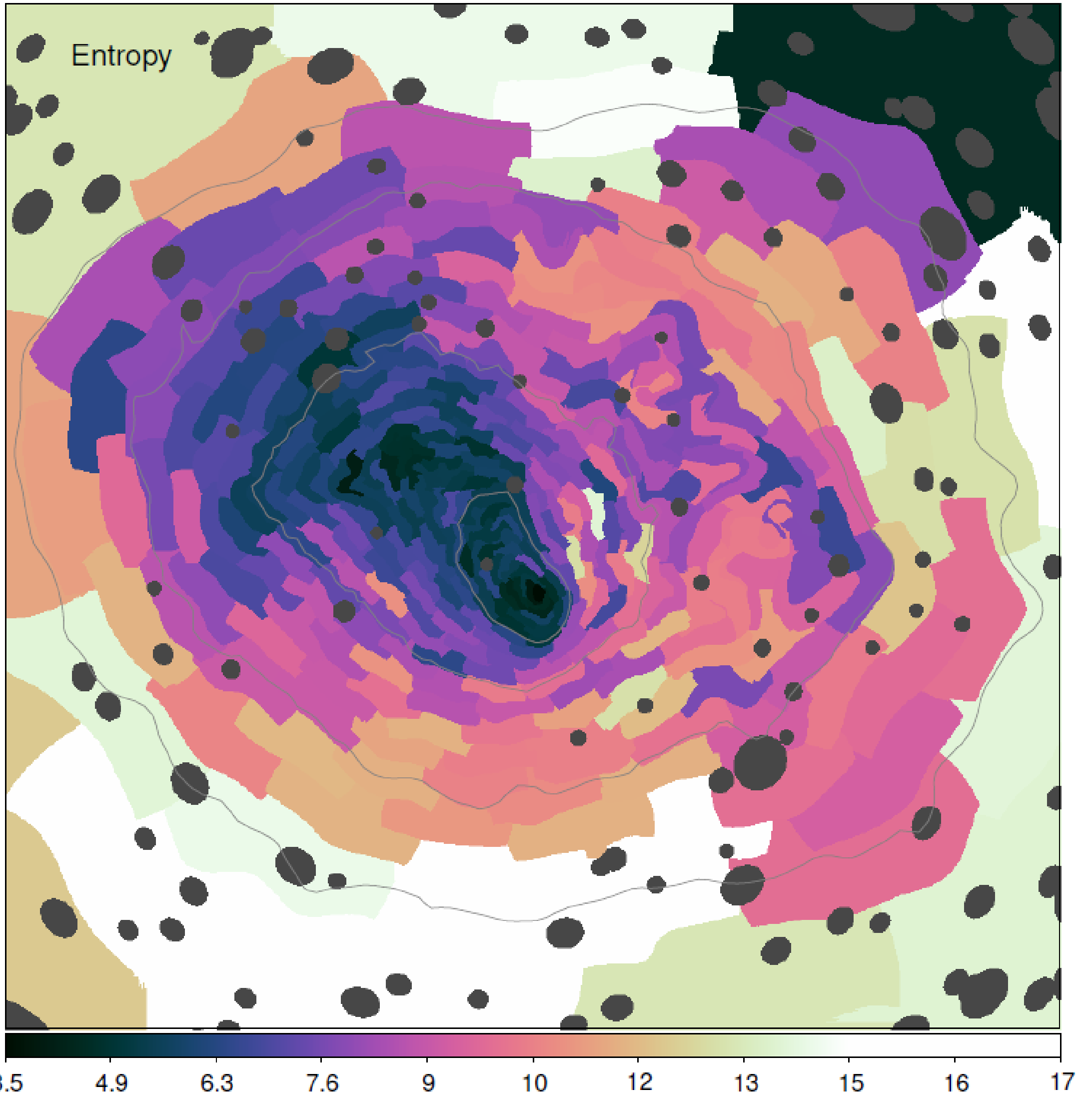
Smooth mapping technique: ellipse mapping

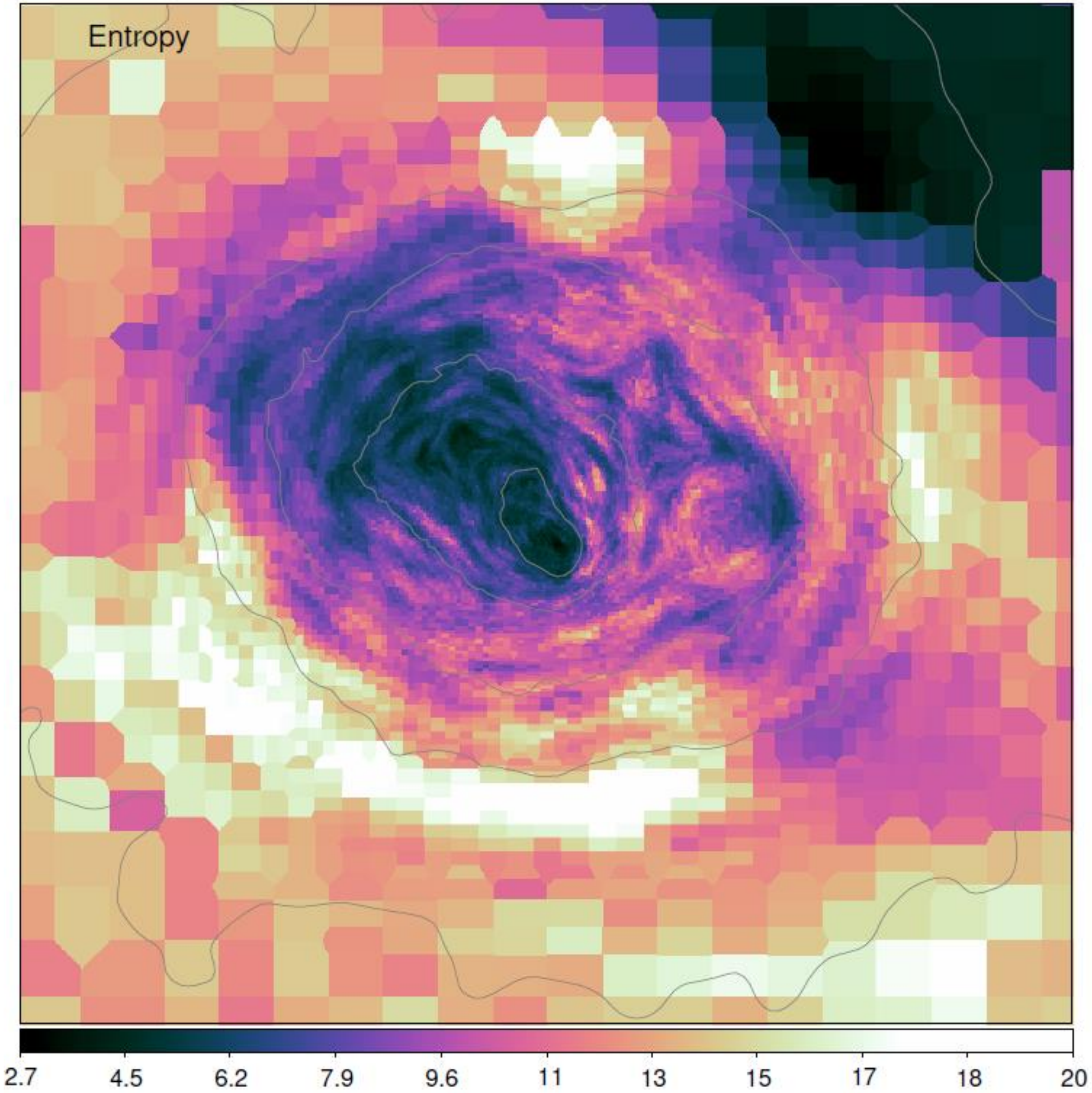
- Some existing smooth mapping techniques include
  - Adaptive smoothing (e.g. Markevitch 2000)
  - Wavelets (e.g. Bourdin et al. 2004)
- In Sanders et al. (2021), we used ellipse mapping – a smooth spectral mapping technique similar to contour binning:
  1. Make an adaptively smoothed X-ray image
  2. On a set of grid points, fit ellipses to image, with size determined by S/N ratio, and aspect ratio/angle to minimize pixel variance within ellipse
  3. Compare sets of neigbouring ellipses in X and Y directions
     1. Compute distance as a function of size of ellipse on axis
     2. If it's larger than some value, insert extra grid points (ellipses) along respective axes
     3. Repeat until no longer large separations
  4. Extract and fit spectra from ellipses. For a pixel in output, show result from closest ellipse.

Sanders et al. (2021)

Adaptive Gaussian smoothed eROSITA RGB image of Abell 3266

eROSITA entropy maps of A3266





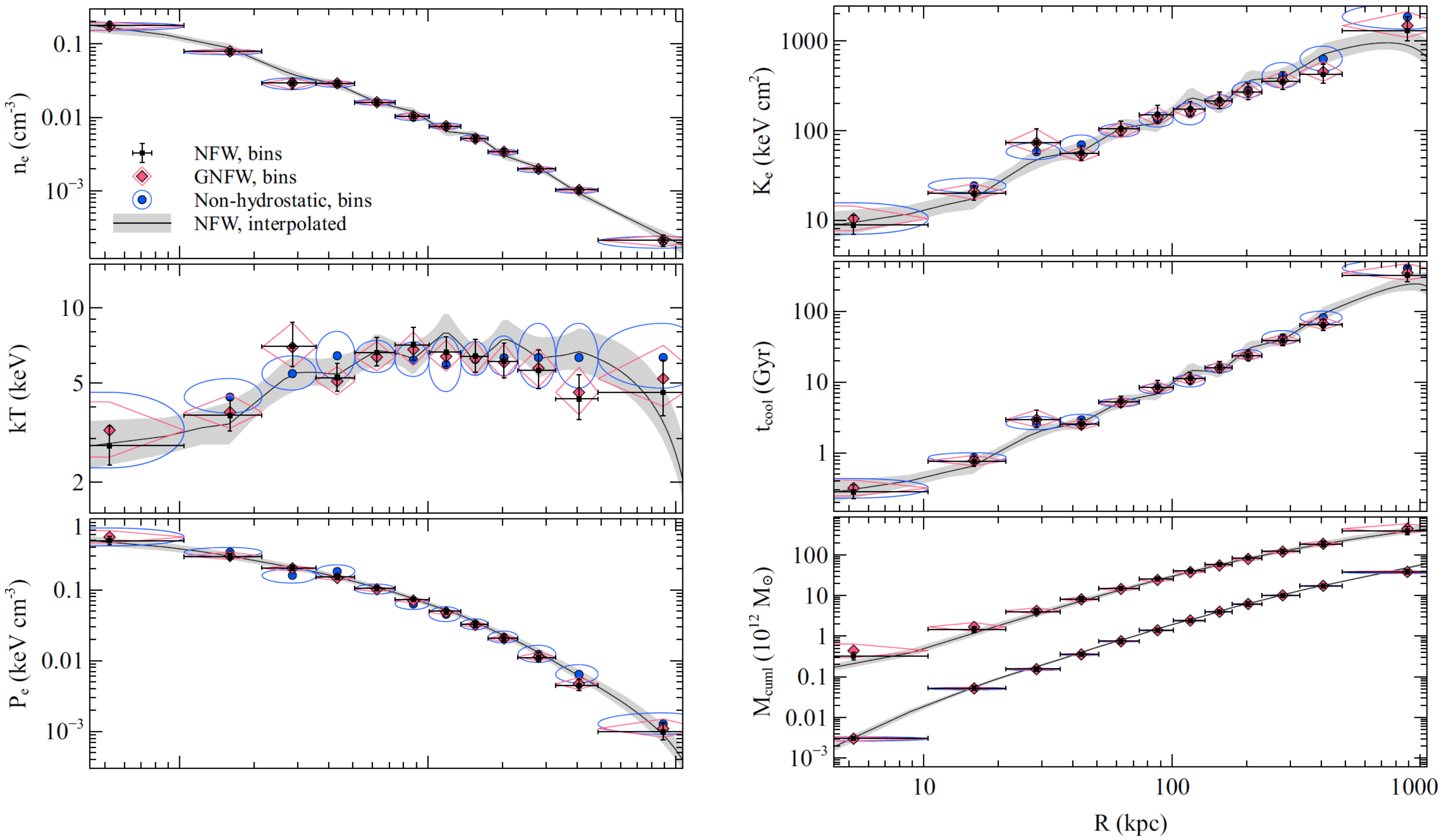
Contour binning (above) vs ellipse mapping (right)
Sanders et al. (2021) [note: size scales not same!]

Forward modelling techniques

- Useful for getting model parameters
- Can take account of projection and fit multiple datasets simultaneously
- Codes include
  - Model spectra with projection (Xspec PROJCT model)
  - Model object as set of Gaussian blobs (Peterson et al. 2007; Frank et al. 2013)
- MBProj2 (Sanders et al. 2018) and MBProj2D (designed for eROSITA)
  - Model surface brightness profiles (MBProj2) or images (MBProj2D) of clusters in multiple energy bands
  - Density profile model
  - Temperature or mass model (assuming hydrostatic equilibrium to convert mass to temp.)
  - Model multiple clusters (including positional parameters) and point sources, in case of MBProj2D
  - Use MCMC and priors to study profiles

https://github.com/jeremysanders/mbproj2
https://github.com/jeremysanders/mbproj2d

Example: SPT-CLJ0000-5748 (z=0.702)



Around 1500 Chandra counts fitted with MBProj2

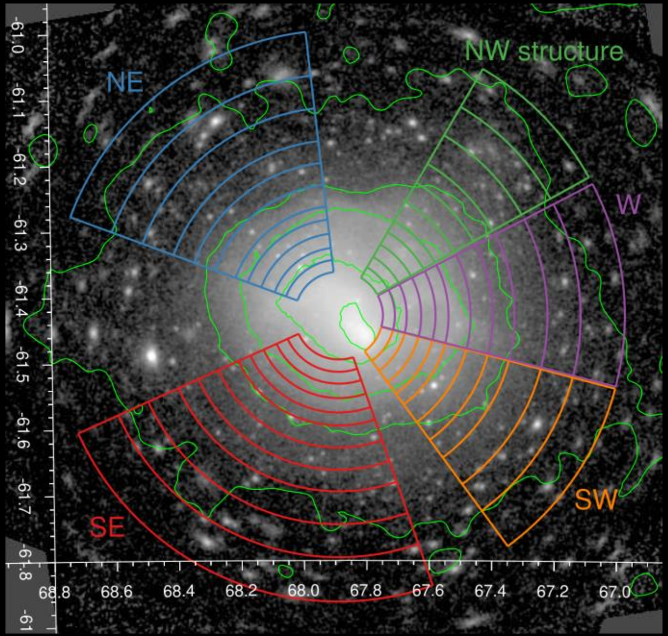
Showing consistent results from binned and interpolated models

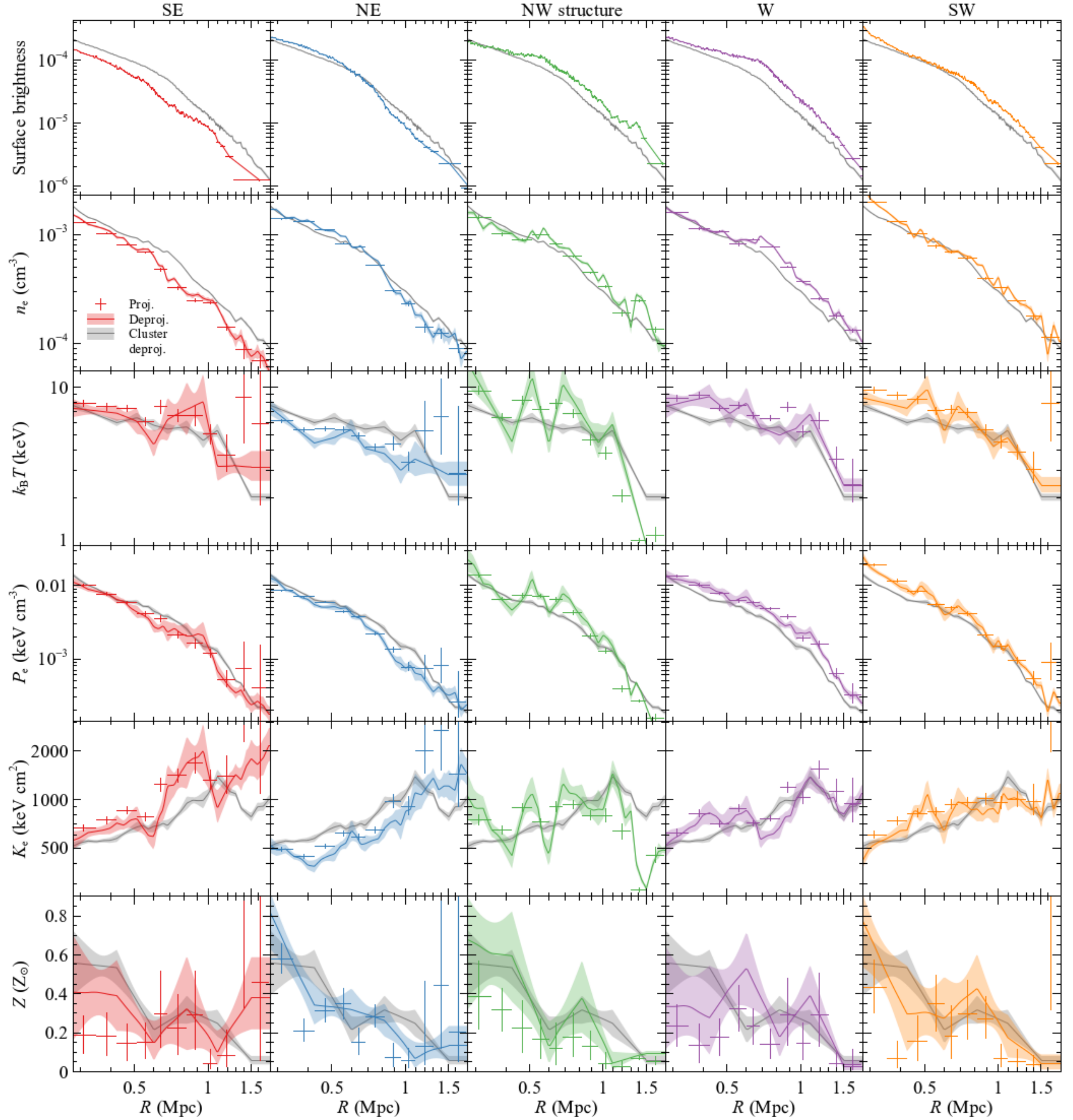
Showing different mass models and effect of hydrostatic equilibrium

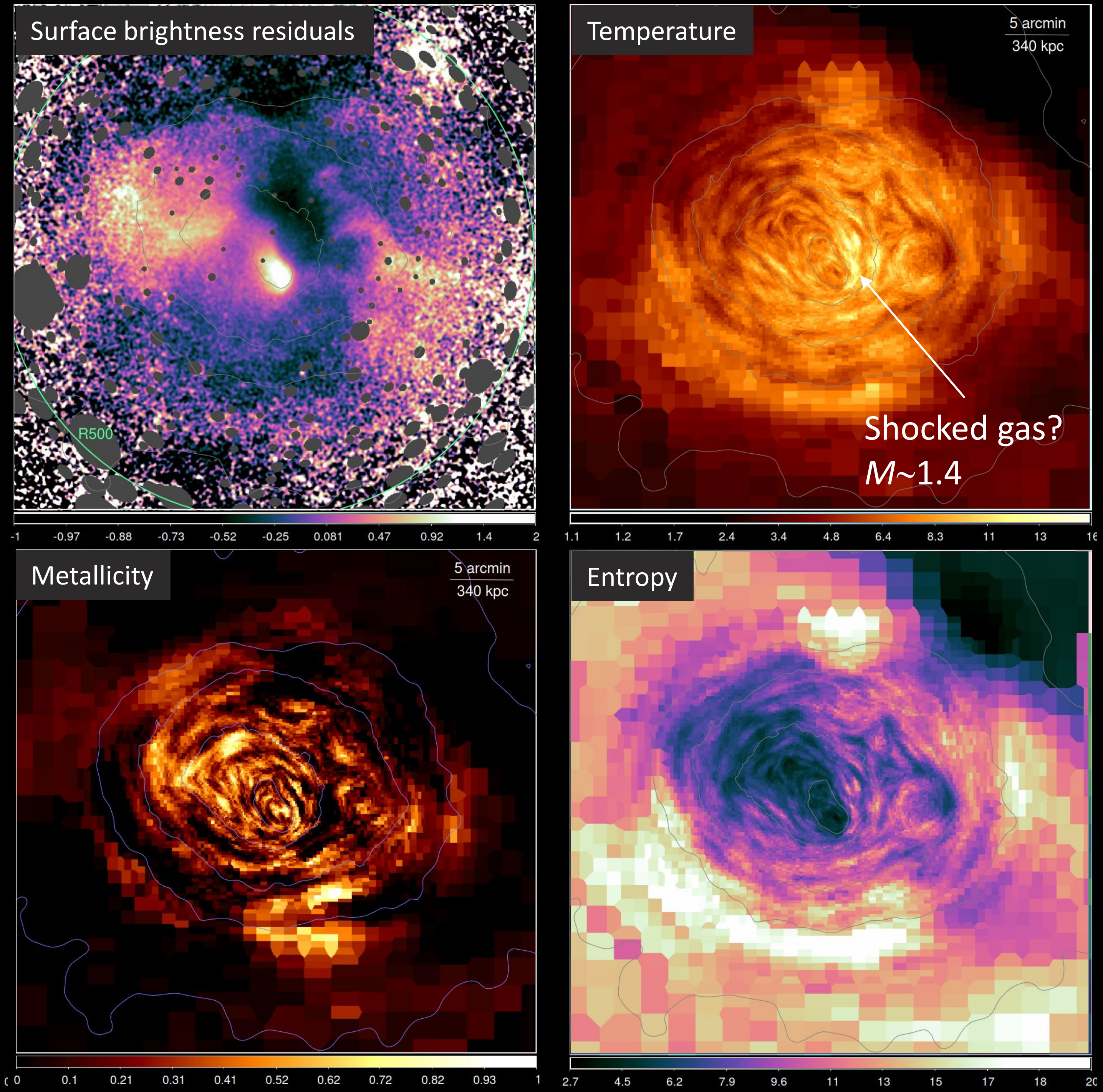
Sanders et al. (2018)

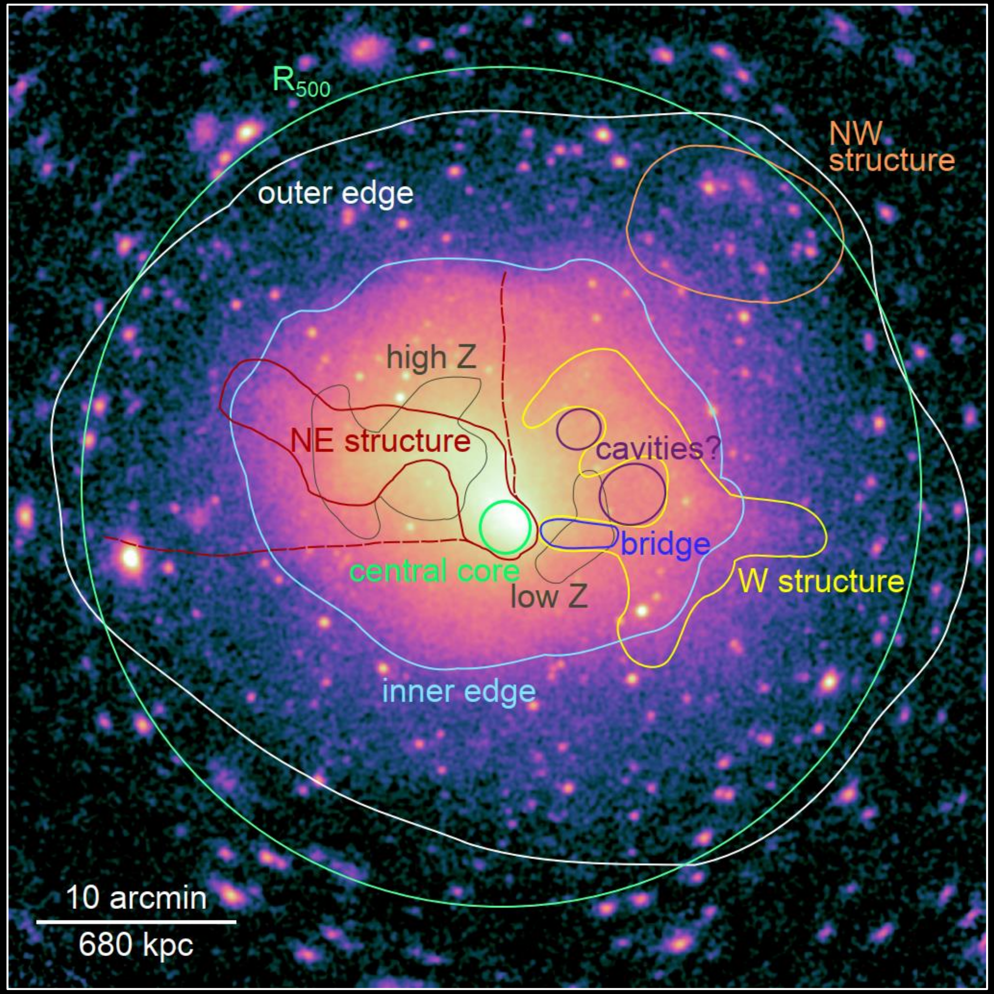
Codes

- GGM and Adaptive GGM edge filtering
- Contour binning
- Ellipse mapping
- MBProj/MBProj2D


NE
NW structure
W
SE
SW
-61.0
-61.1
-61.2
-61.3
-61.4
-61.5
-61.6
-61.7
-61.8
68.6
68.4
68.2
68.0
67.8
67.6
67.4
67.2
67.0


SE
NE
NW structure
W
SW
Surface brightness
n_e (cm^{-3})
Proj.
Deproj.
Cluster deproj.
$k_B T$ (keV)
P_e (keV cm^{-3})
K_e (keV cm^2)
Z ($Z_\odot$)
R (Mpc)





Thermodynamic maps, generated by fitting spectra extracted with ellipses which follow the surface brightness contours (with adaptive size)