Imaging Analysis:
Point-Like Sources and Diffuse Emission

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Introduction

- Imaging analysis _ imaging spectroscopy
  - Few X-ray detectors are without spectroscopic capabilities
  - Surface photometry and spectroscopy inseparable
- Concentrate on “soft” X-ray studies (E<10 keV)
- Principals are mission/software/detector independent

Introduction

Event lists contain [time, x, y, ~E] for every event

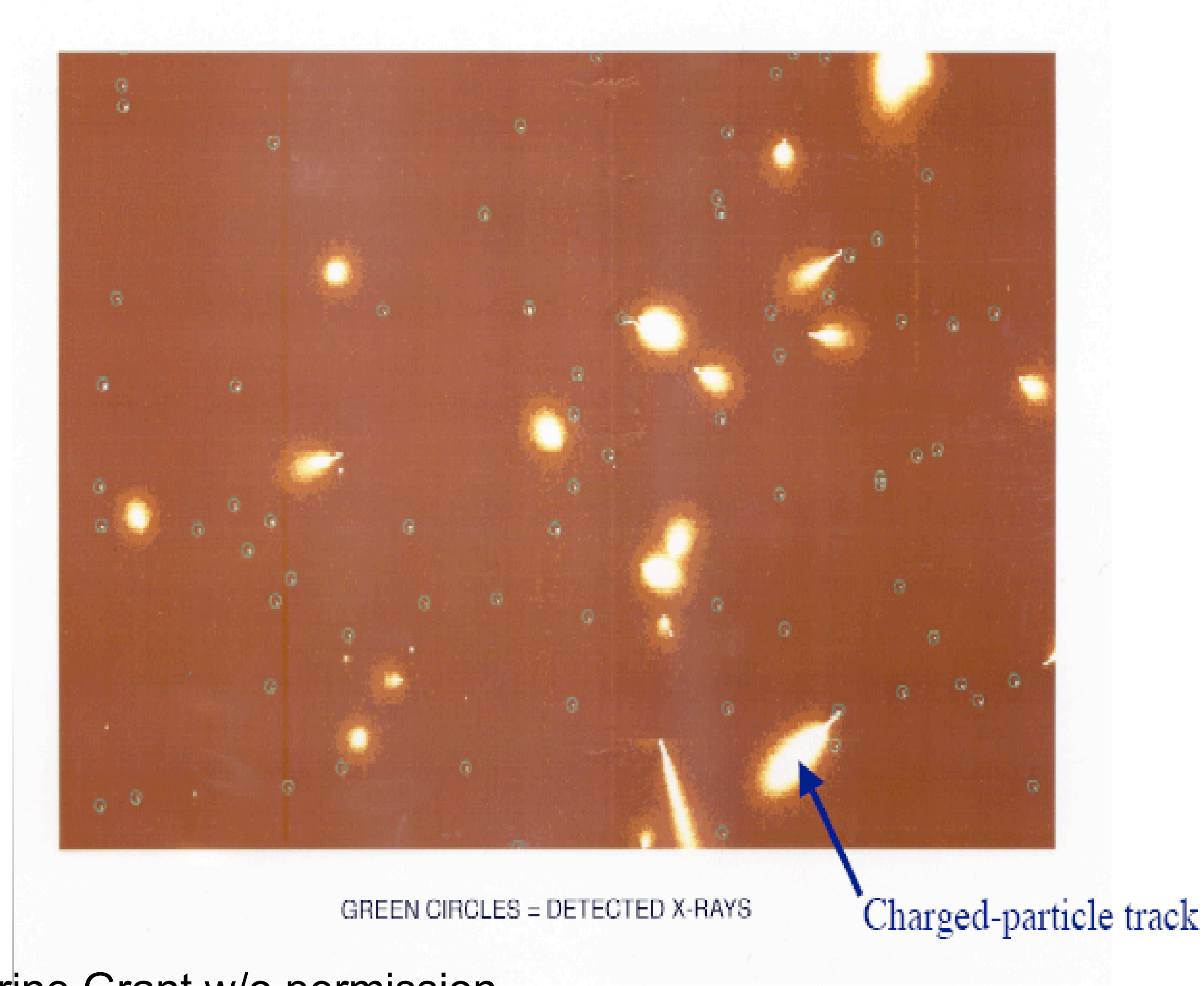
What you don't know about each event is:

- Whether a photon or an energetic particle
- What direction the photon came from
- Origin along the line of sight

What you want to do is:

- Remove the non-source events (statistically)
- Convert number of observed _ to number of emitted _

ACIS X-ray/Particle Discrimination



From Catherine Grant w/o permission

Definitions

- Non-Cosmic Background _ Instrumental Background
  - Events not due to photons entering the telescope
  - Typically cosmic ray interactions with detector or
  - X-rays produced by cosmic ray interactions with other stuff
- Cosmic Background
  - Non-source photons entering the telescope
  - Other emitting components along the line of sight
    - Hot Galactic ISM and the Galactic halo
    - X-ray Background due to unresolved AGN

Definitions

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  - X-rays prod other stuff
- Cosmic Back
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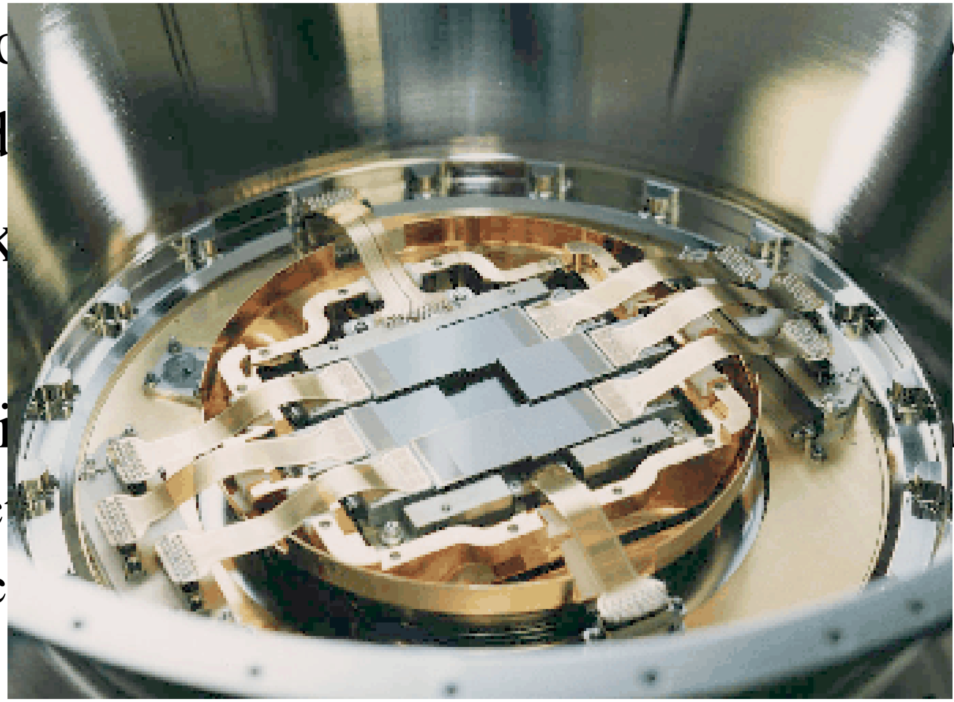
  - Other emitti t
    - Hot Galac
    - X-ray Bac

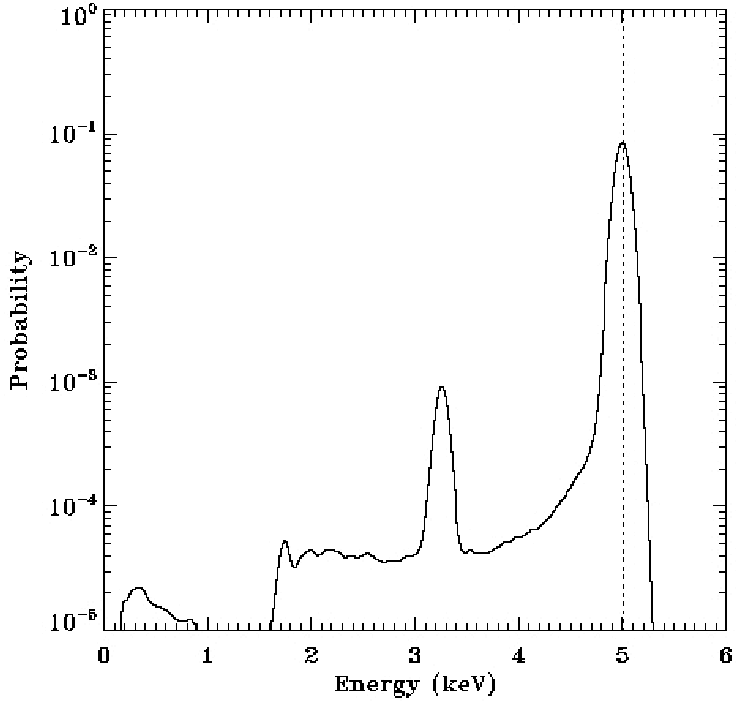


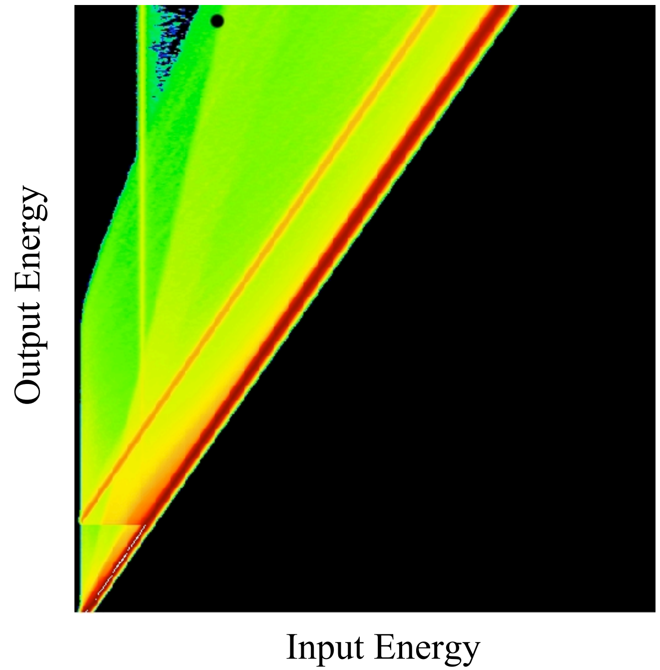
Definitions

- Response: Probability that a photon of energy E entering the telescope is recorded by the detector.
  - $P_T(\text{mirror})P_T(\text{filters})\cdots P_D(\text{detector})$
  - May include geometric factor for size of the detector element compared to the PSF
  - Usually contained in the Auxiliary Response File (ARF)
  - In units of cm^2

Definitions

- Redistribution: Probability that a photon of incident energy E is recorded at energy E'
  - For every E' must sum over all possible input E
    _convolution or multiplication by 2-dimensional matrix
  - Usually contained in the Redistribution Matrix File (RMF)





Observed = (Input_Response)ΥRedistribution

Observed = (Input_Response)YRedistribution

How to get Input spectrum given the observed spectrum?

- Inversion is difficult and the results are unstable

Observed_Input

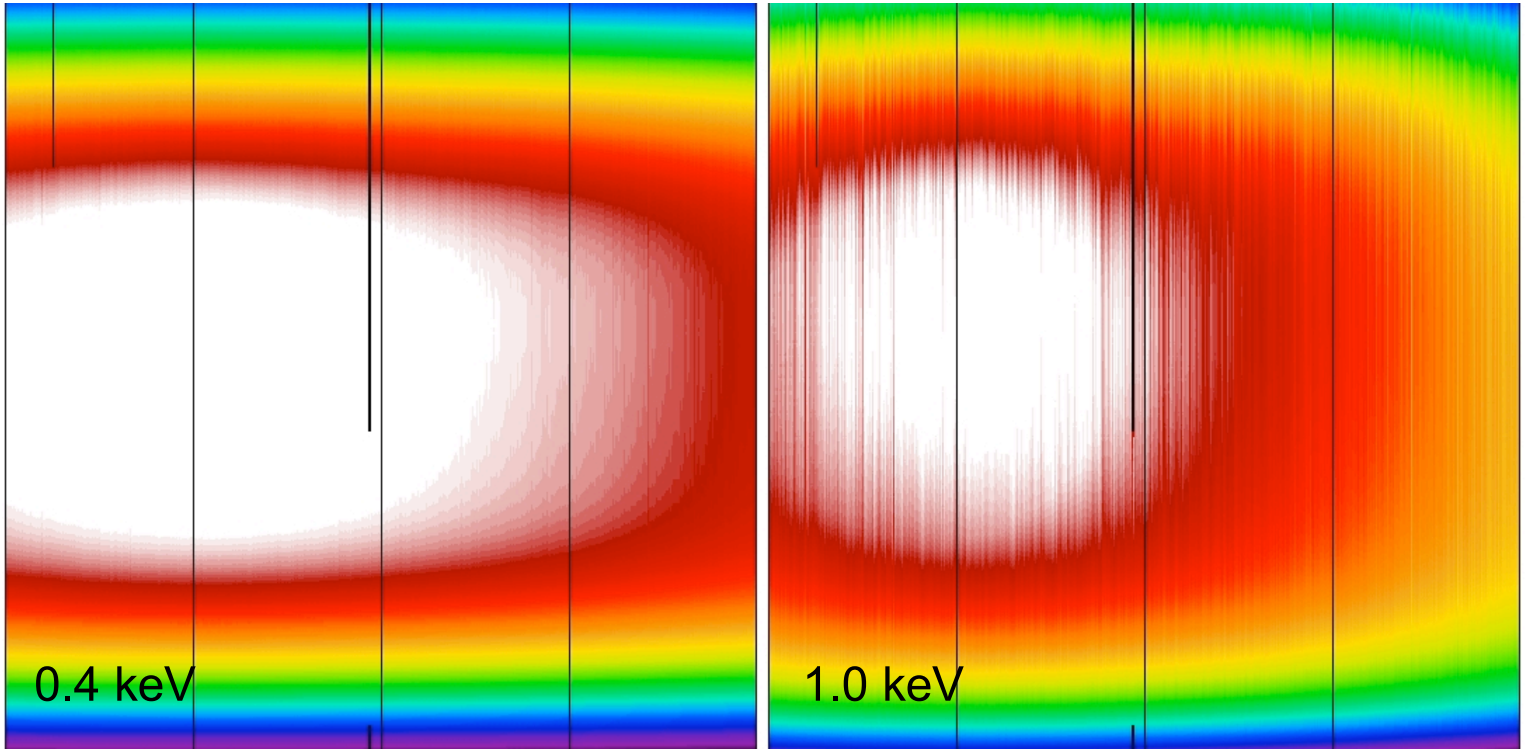
Model
Model
Model
Model
Model

Observed

Spectral fitting: XSPEC, Sherpa, etc.

Multi-element detectors

- Response varies with position
  - Throughput of telescope optics varies with off-axis angle
  - Blocking filter transmission varies with position
  - Response of detector varies with position
  - Spatial variation varies with Energy



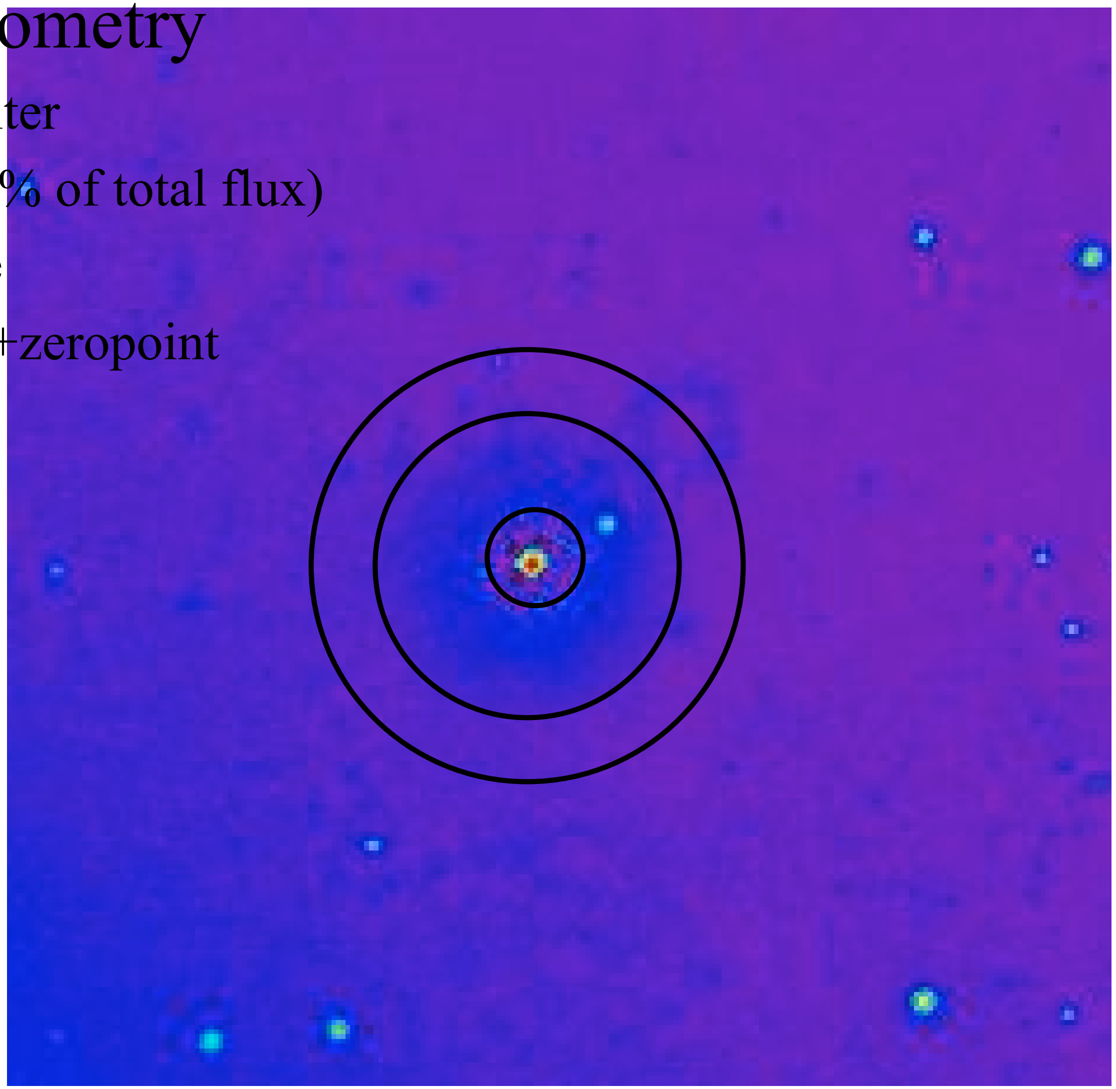
Multi-element detectors

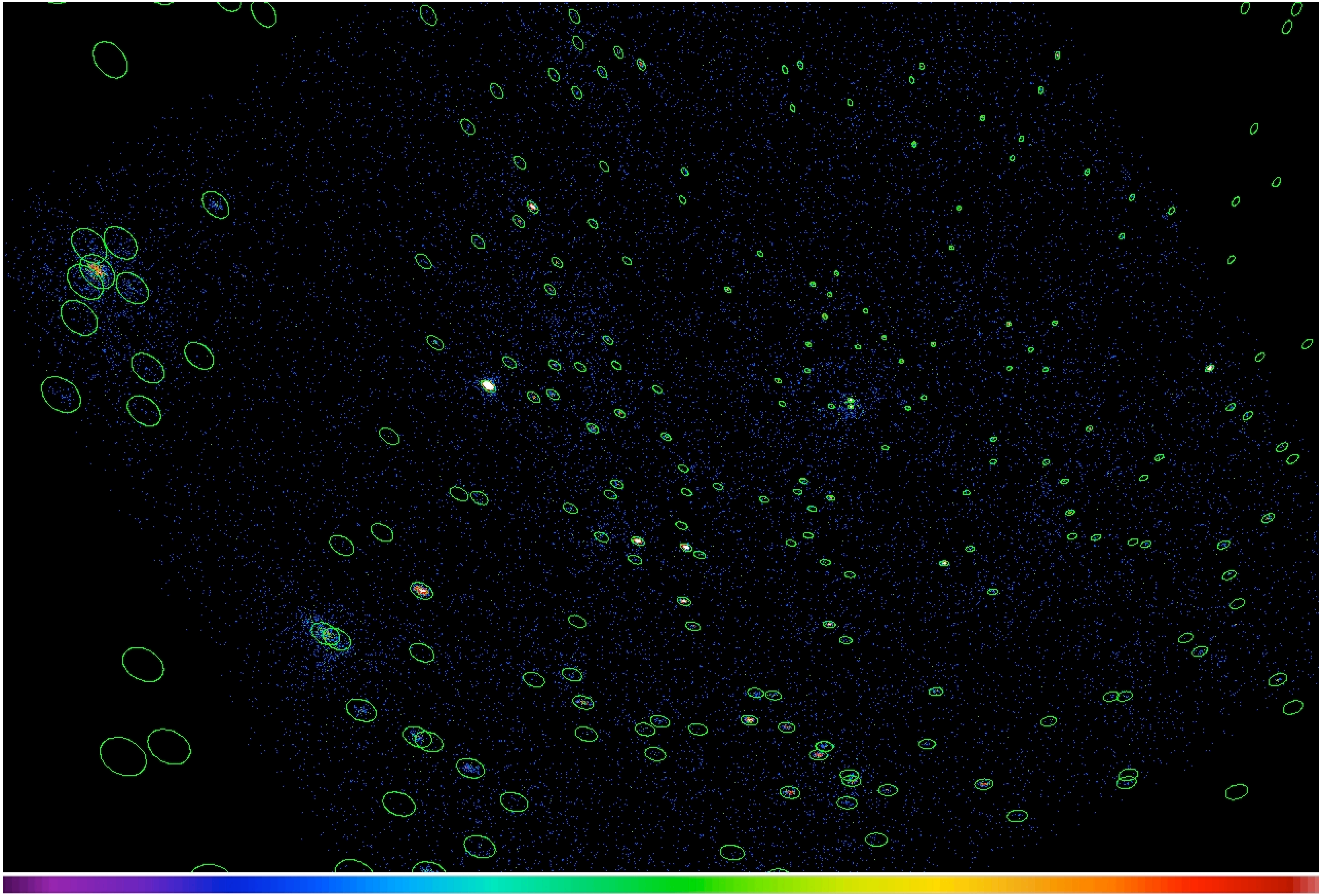
- Response varies with position
  - Throughput of telescope optics varies with off-axis angle
  - Blocking filter transmission varies with position
  - Response of detector varies with position
  - Spatial variation varies with Energy
- Redistribution varies with position
  - Charge-transfer inefficiency

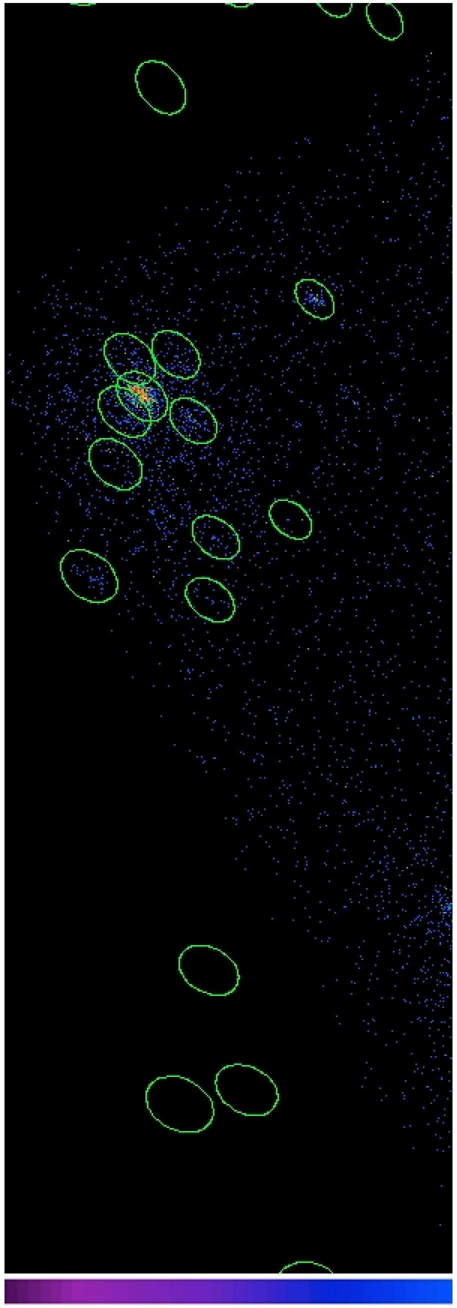
Point Source Analysis

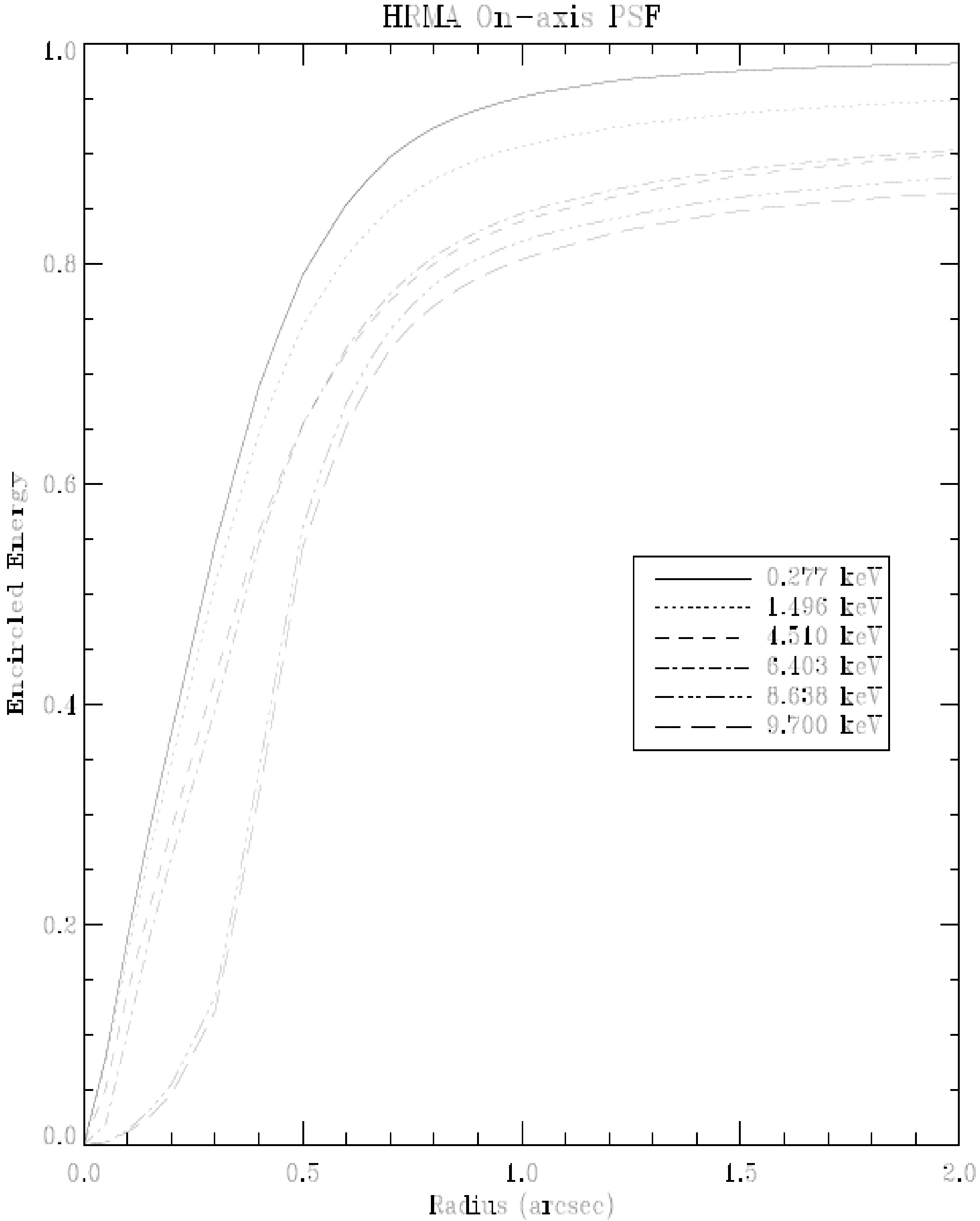
Classical optical photometry

1. Band-pass defined by filter
2. Set aperture (contains X% of total flux)
3. Set background aperture
4. Mag=Log(source-back)+zeropoint

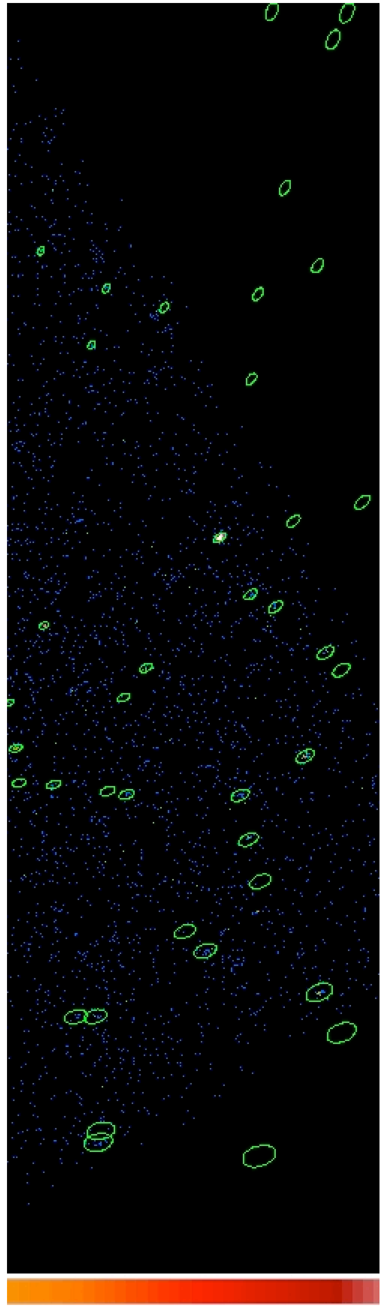








HRMA On-axis PSF
Encircled Energy
Radius (arcsec)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
0.277 keV
1.496 keV
4.510 keV
6.403 keV
8.638 keV
9.700 keV



Point Source Analysis

Similar to classical optical photometry/spectroscopy but…

1. Choice of band-pass is yours

   Not determined entirely by instrumental filters

2. Aperture correction

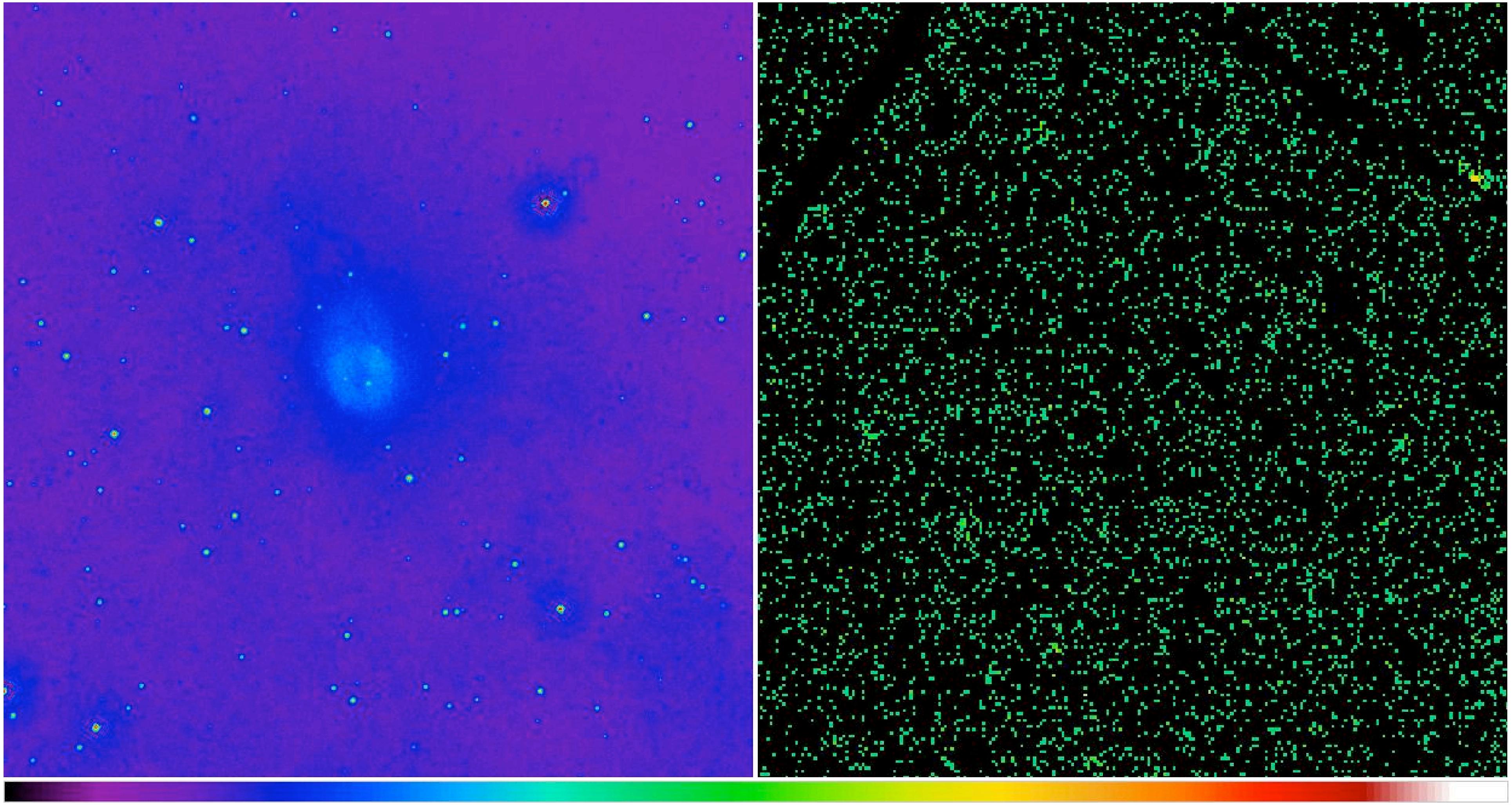
   strongly dependent on location and Energy

3. Different statistical regime
   - Small number statistics
   - Setting background region is more difficult
4. Zeropoint (response) strongly dependent on location

Point Source Analysis

Similar to classical optical photometry/spectroscopy but…

1. Choice of band-pass is yours



Point Source Analysis

1. Source detection:

   Sliding box, Convolution techniques, Tesselation techniques

2. Set aperture to include large fraction of source energy
3. Set background region

   Not too small or value will be uncertain

   Not too large or will not represent the local background

   Source of background *may* not be important

4. Create response & redistribution functions for source

   Sometimes will need to create for background region as well

5. Fit the spectrum

   For photometry apply a spectral shape

Point Source Analysis - Tools

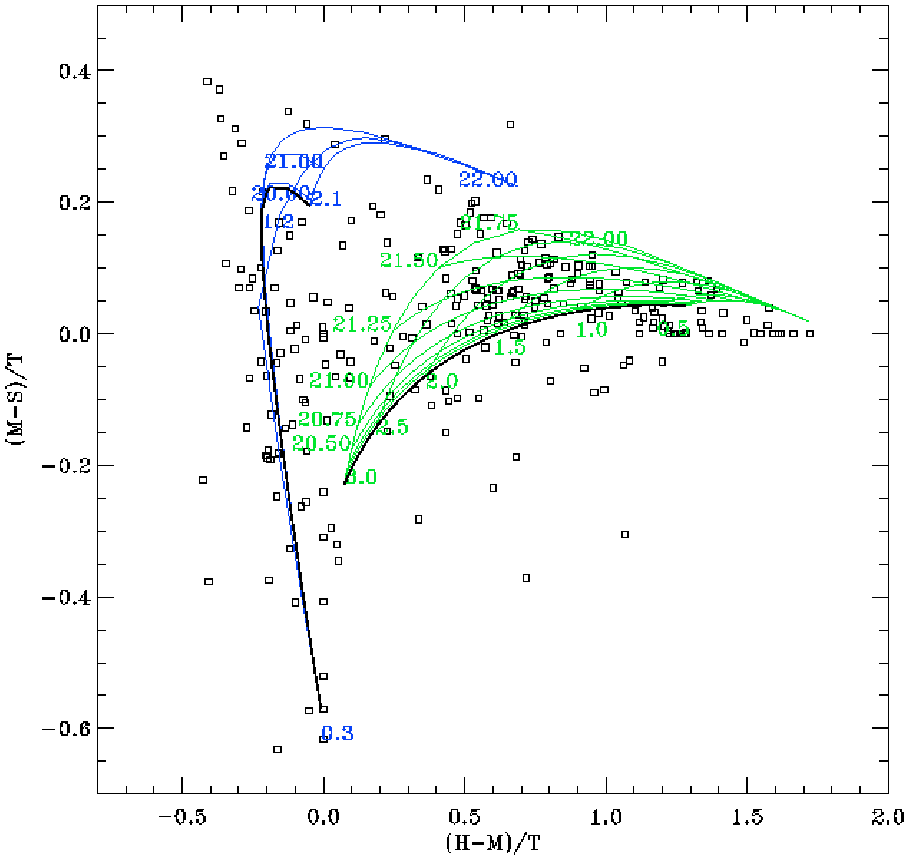
Tools are mostly mission specific

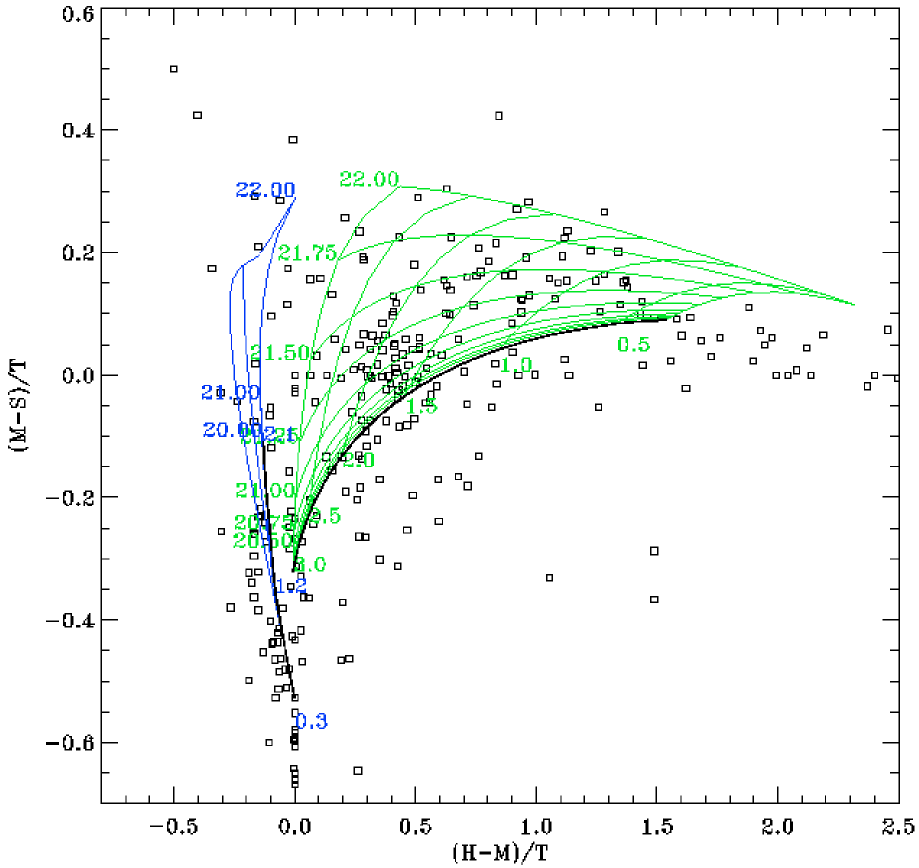
- Chandra
  - CIAO – stand alone software, requires step-by-step application
  - ACIS-Extract – IDL-based, sophisticated tools for analysis of large number of sources
- XMM-Newton
  - SAS – stand-alone software, quasi-automatic
- Suzaku, ASCA, ROSAT, Swift
  - HEASoft – stand alone tools, requires step-by-step application, lacks source detection package
  - Sextractor
  - X-Assist

Point Source Analysis - Applications

Color-color Diagrams: to identify types of sources by their spectral shape.

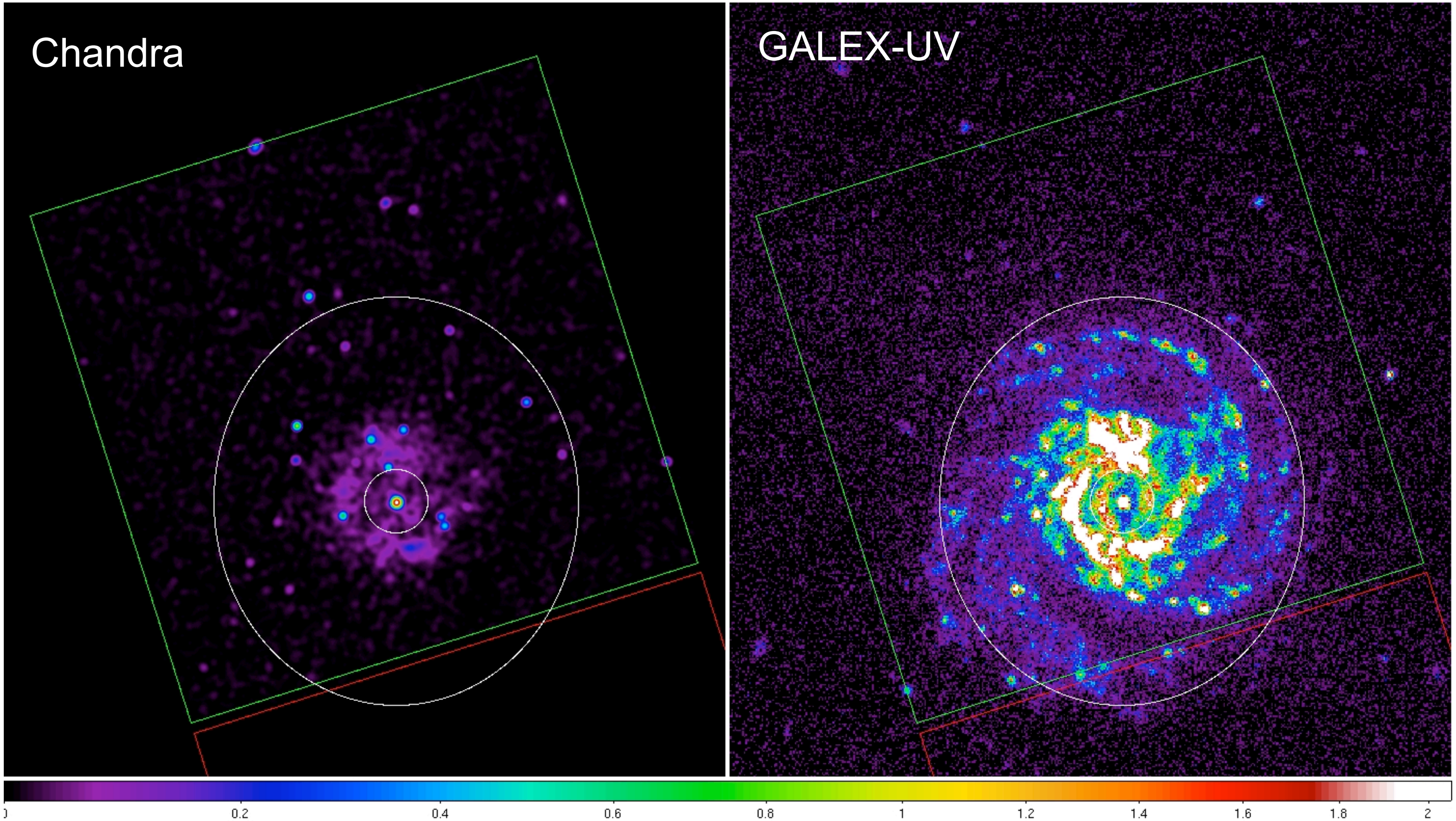
Band choice is crucial





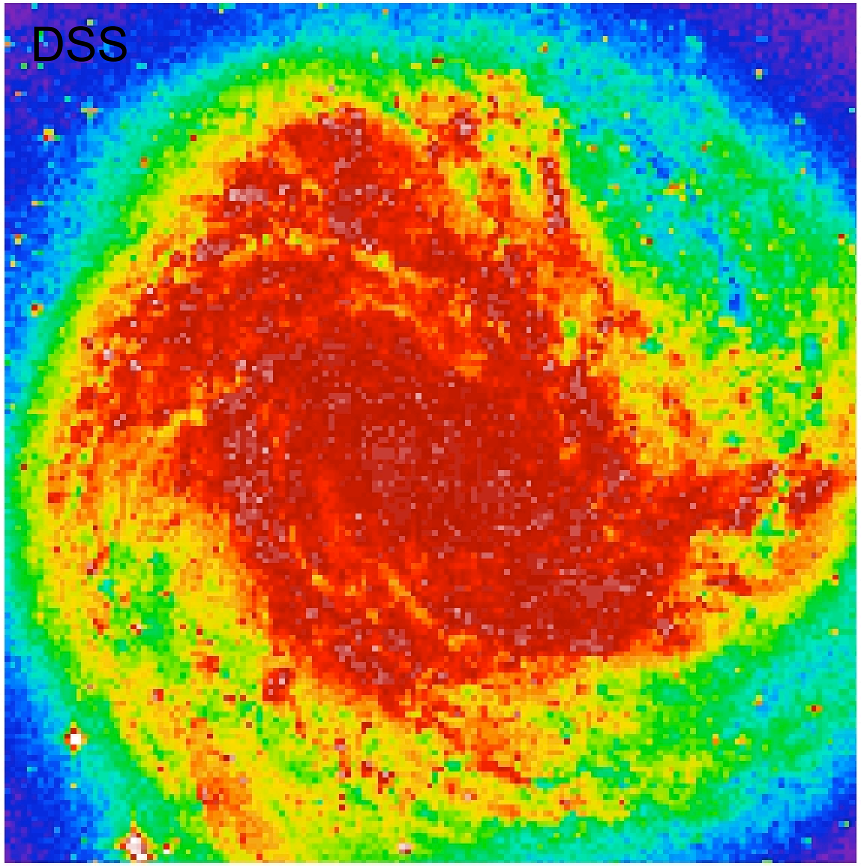
Diffuse Analysis-Motivation

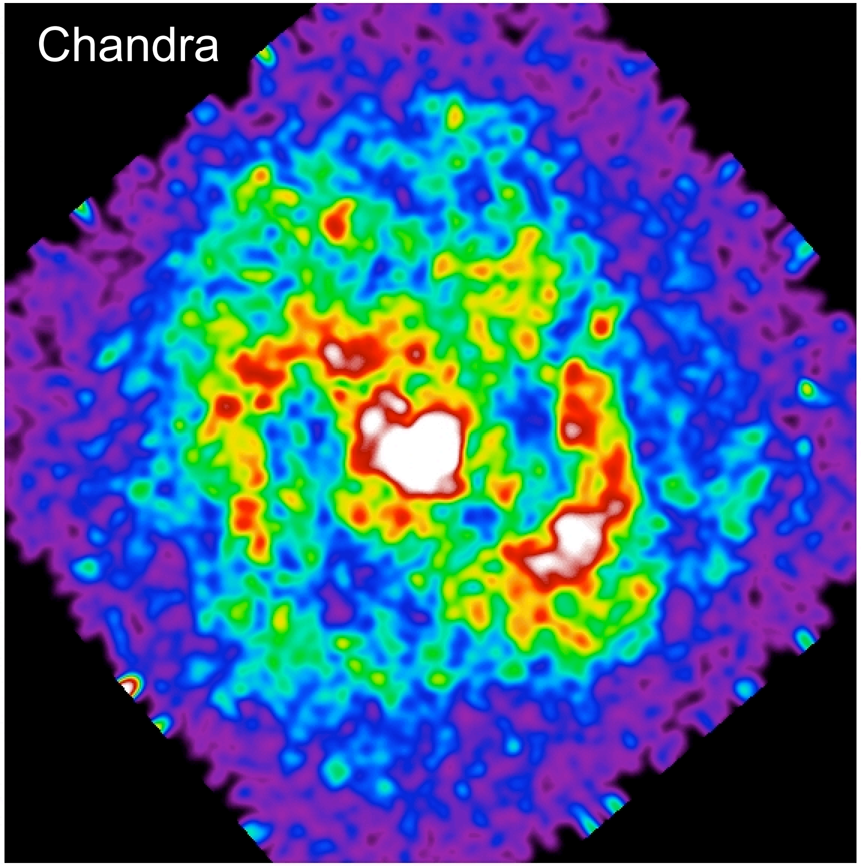
- NGC4303 – galaxy well placed in FOV

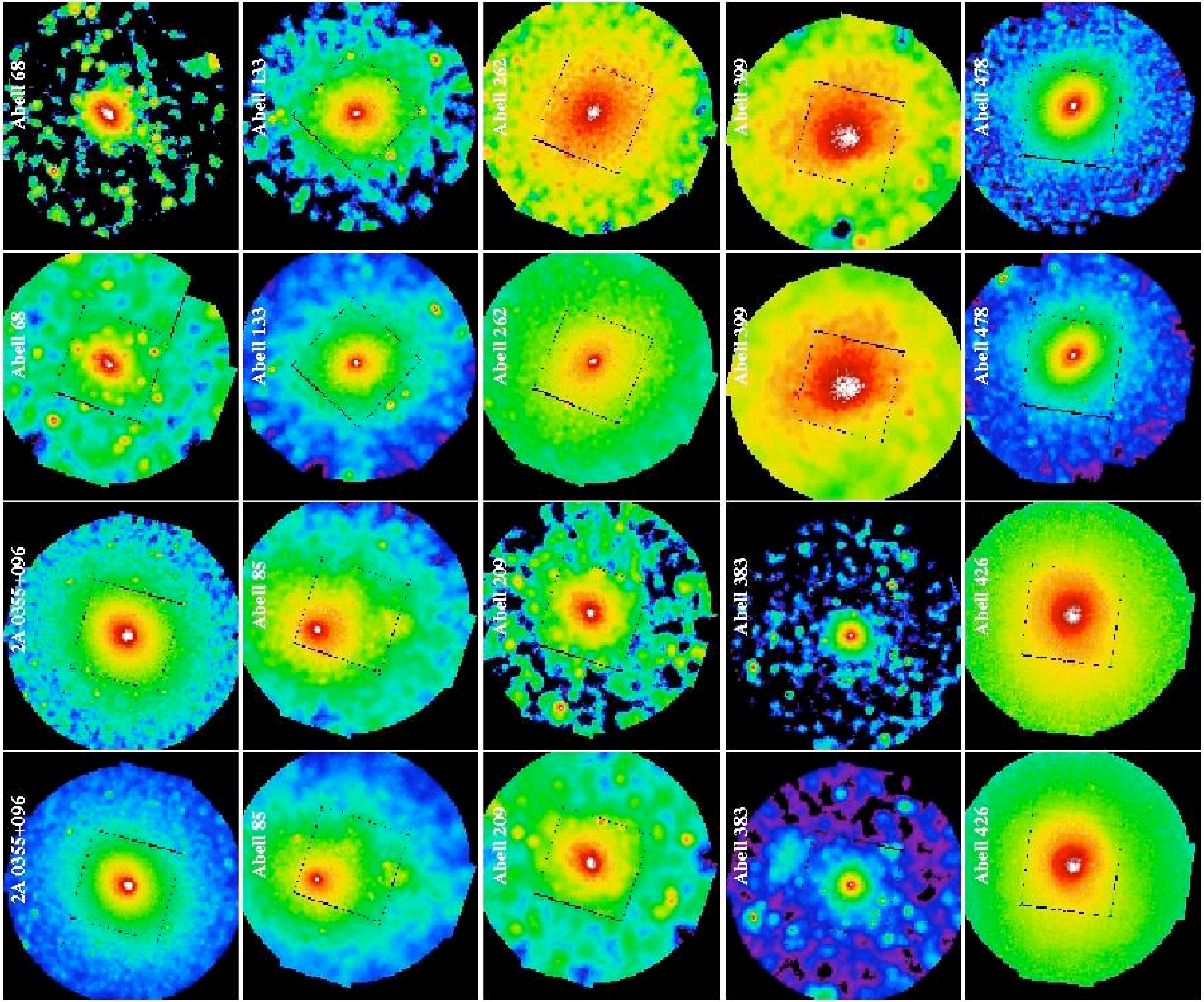


Diffuse Analysis-Motivation

- NGC5236 (M83) fills the FOV
  - Optical (and X-ray?) extends beyond edge of detector






Abell 68
Abell 133
Abell 262
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Abell 478
Abell 68
Abell 133
Abell 262
Abell 399
Abell 478
2A 0355+096
Abell 85
Abell 209
Abell 383
Abell 426
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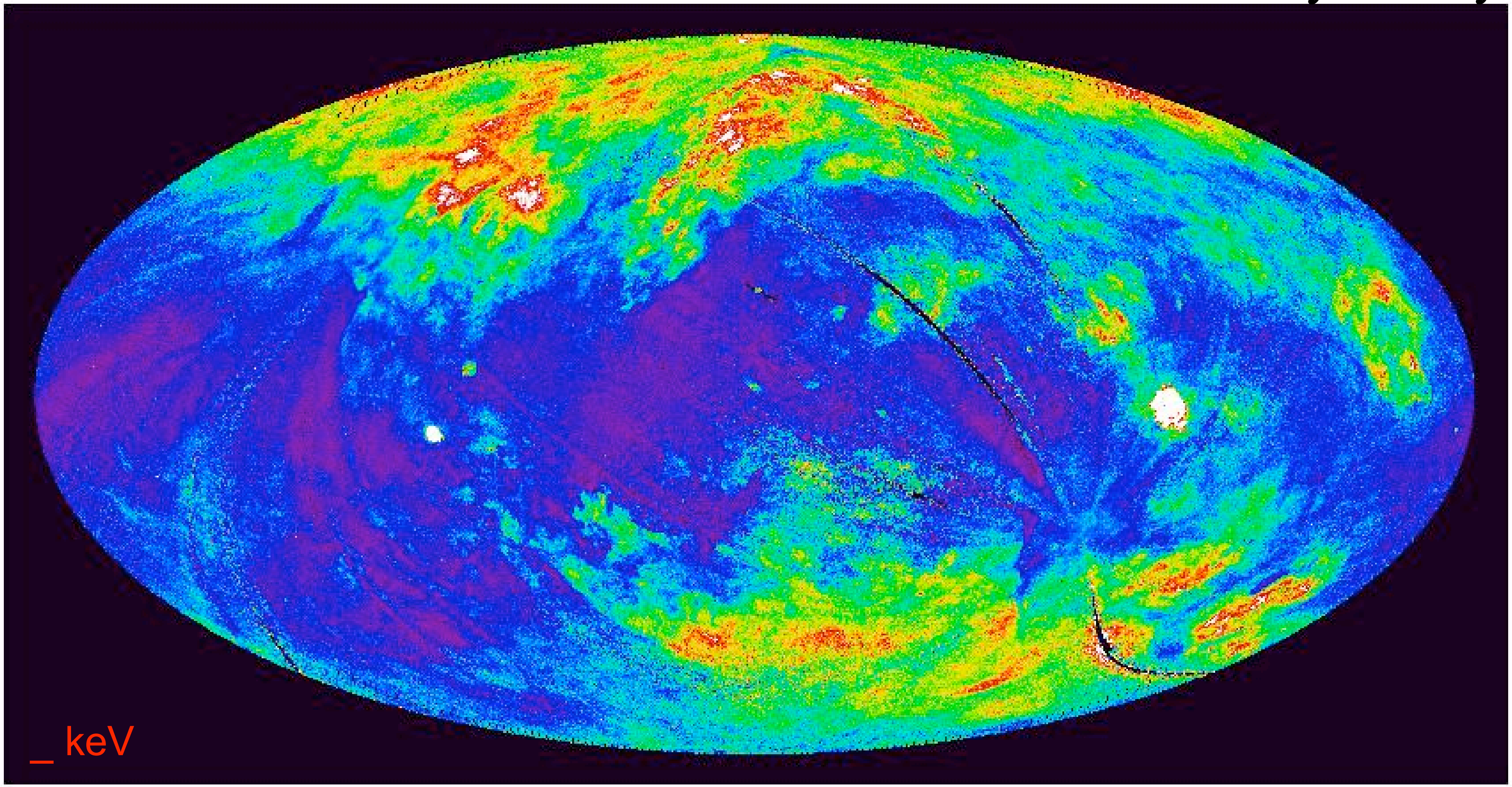
Diffuse Analysis-Motivation

ROSAT All-Sky Survey



- One must use non-local backgrounds
  - Different responses and different background components
- Sometimes there is no background region at all

Diffuse Analysis-Introduction

Imaging – need to know spatial distribution of each background component = knowing spectral distribution

Imaging spectroscopy – need to know spectral distribution of each background component as well

Components:

- Quiescent particle background
- Soft proton contamination
- X-ray background (unresolved AGN)
- Galactic emission (ISM and halo)
- Solar wind charge exchange

All photons vignetted by OTA, Same spatial distribution

Most components identified/quantified spectrally

Spatial and spectral analysis inseparable!!

Diffuse Analysis-Introduction

For each background component

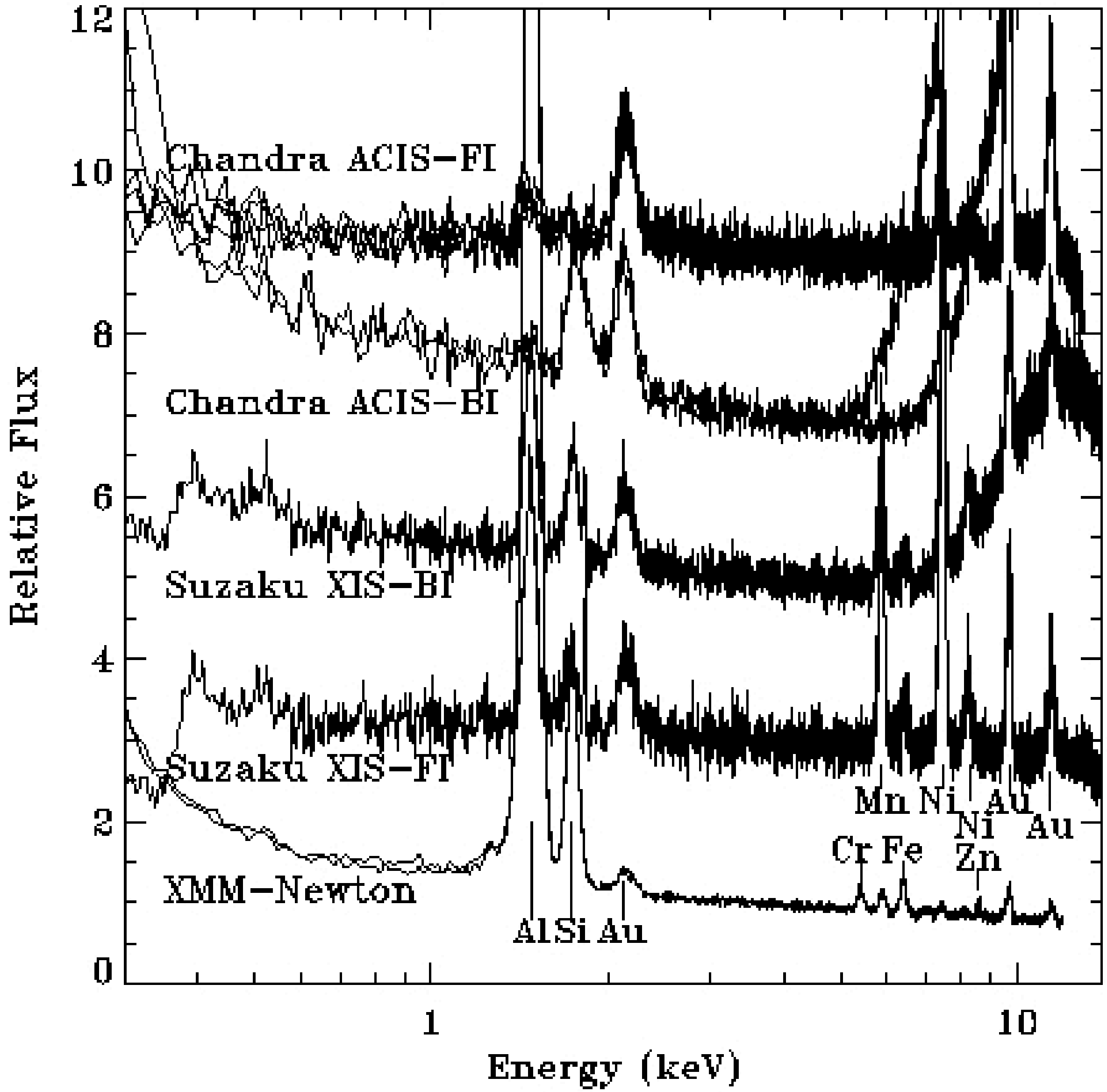
- How we determine its spectral and spatial distribution
- How we determine its strength in our observation
- How we remove it from our data
  - How to include it in our spectral fits

Diffuse Analysis-Backgrounds-Q.P.B.

Quiescent Particle Background

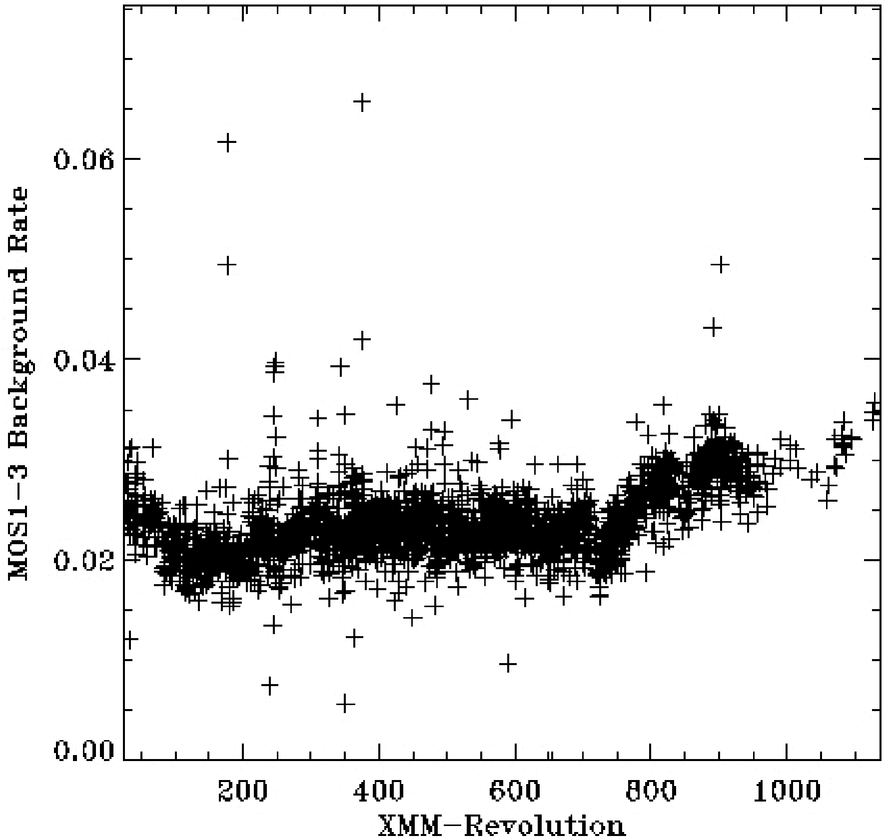
- Due to cosmic rays interacting with the detector and the detector environment, sometimes producing secondary X-rays recorded by the detector.
- Determine the shape of the QPB spectrum: measure the spectrum when the detector is protected from the X-rays but not the cosmic rays.
  - Chandra: move detector from focal plane to under shield
    (the ACIS stowed data)
  - XMM: close the filter wheel
    (the MOS and PN FWC data)
  - Suzaku: observe the dark side of the earth

Diffuse Analysis-Backgrounds-Q.P.B.



Diffuse Analysis-Backgrounds-Q.P.B.

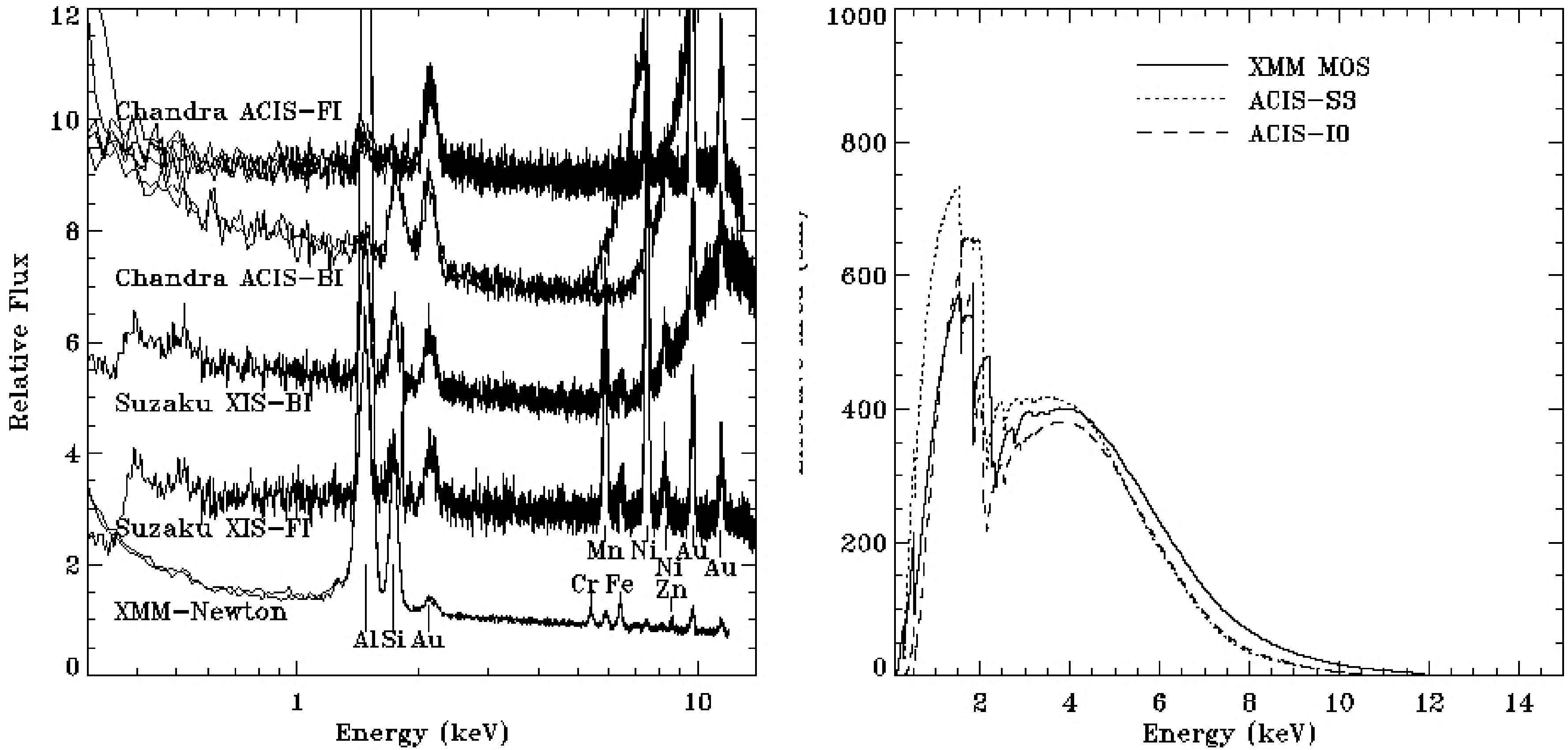
- Strength of QPB variable



- How to determine strength for your observation?

Diffuse Analysis-Backgrounds-Q.P.B.

- Strength of QPB variable



- Measure at E where instrument has no response to X-rays

Diffuse Analysis-Backgrounds-Q.P.B.

- Spatial distribution of QPB:
  - Chandra: distribution flat at all energies (?)
  - XMM: distribution depends on energy
  - Suzaku: smooth gradient over the chip
- These distributions are very different from the distribution of X-ray photons

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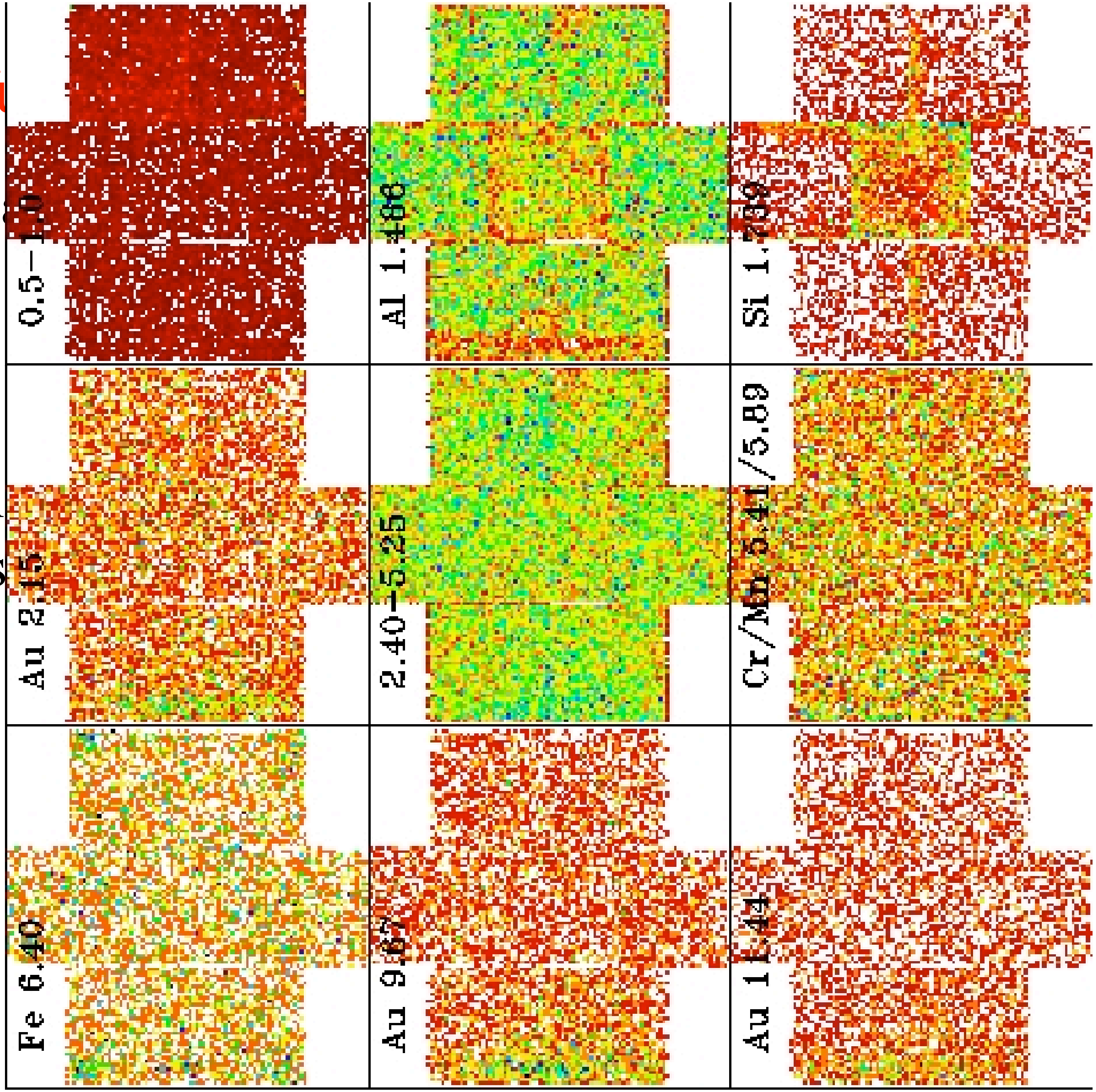
  - –
  - –
  - –
- Th dis



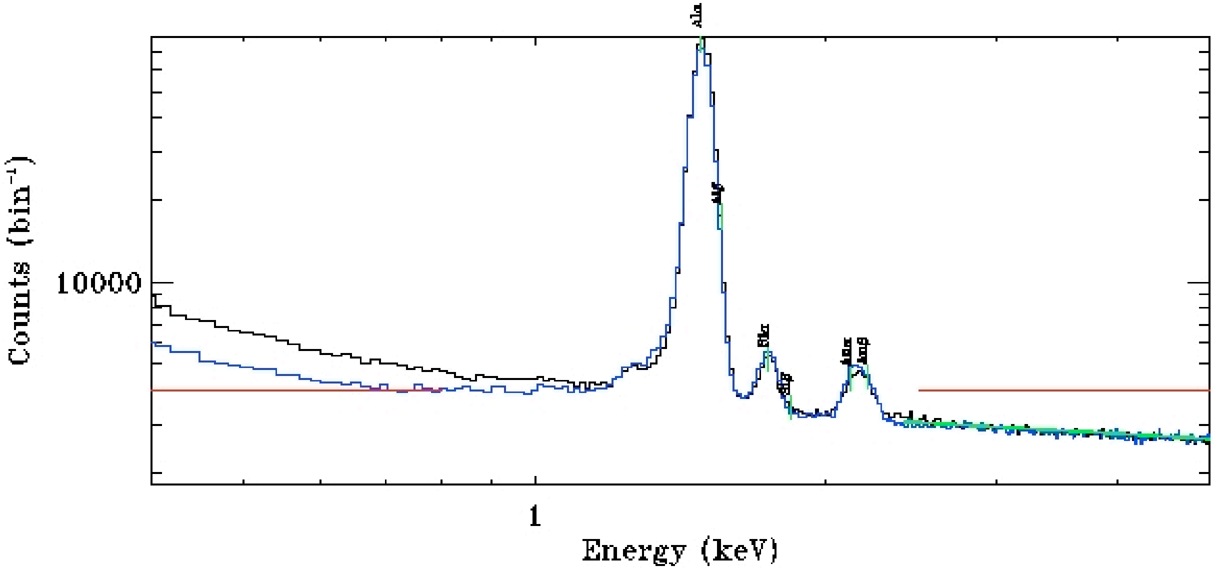
Diffuse Analysis-Backgrounds-Q.P.B.

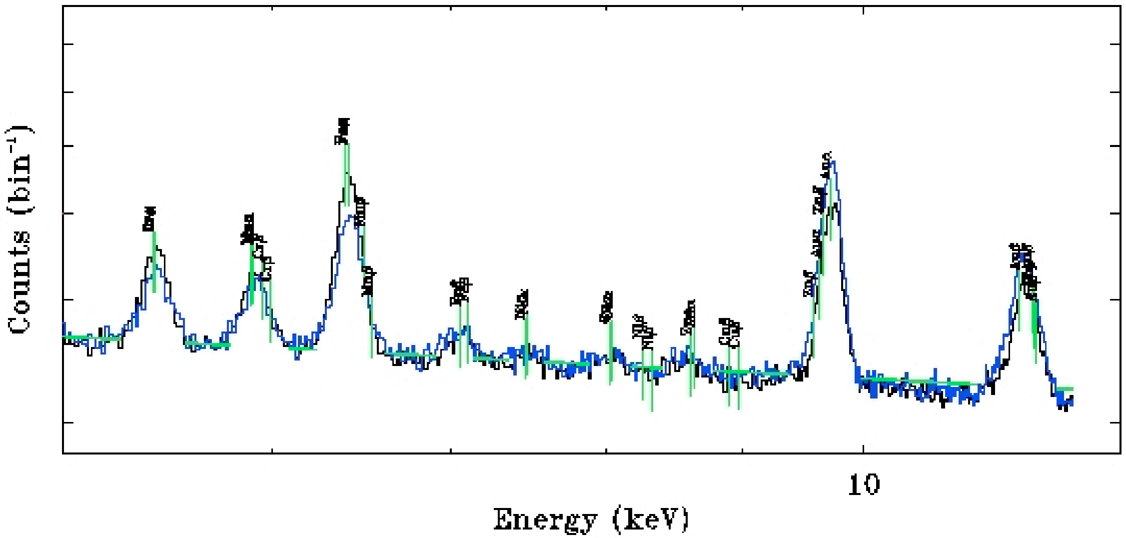
- Shape of QPB spectrum can be time variable
  - Chandra: variation smaller than current data can measure
  - XMM: significant variation on many time scales
  - Suzaku: small(?)

Diffuse Analysis-Backgrounds-Q.P.B.

- Shap
  - Cl
  - X
  - Su

asure





Diffu

- Sh

  –

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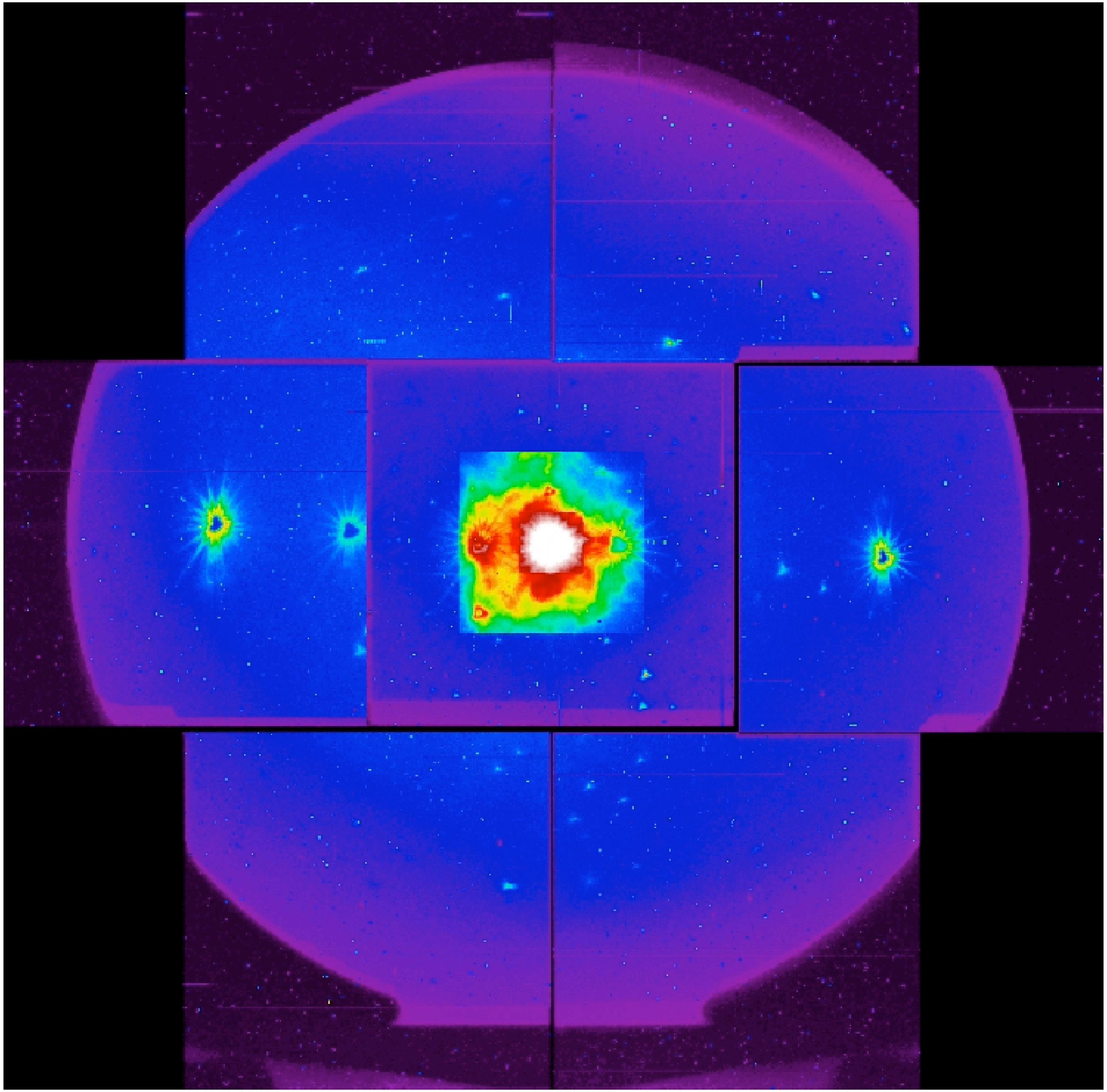


Diffuse Analysis-Backgrounds-Q.P.B.

- Technique for spectral analysis:

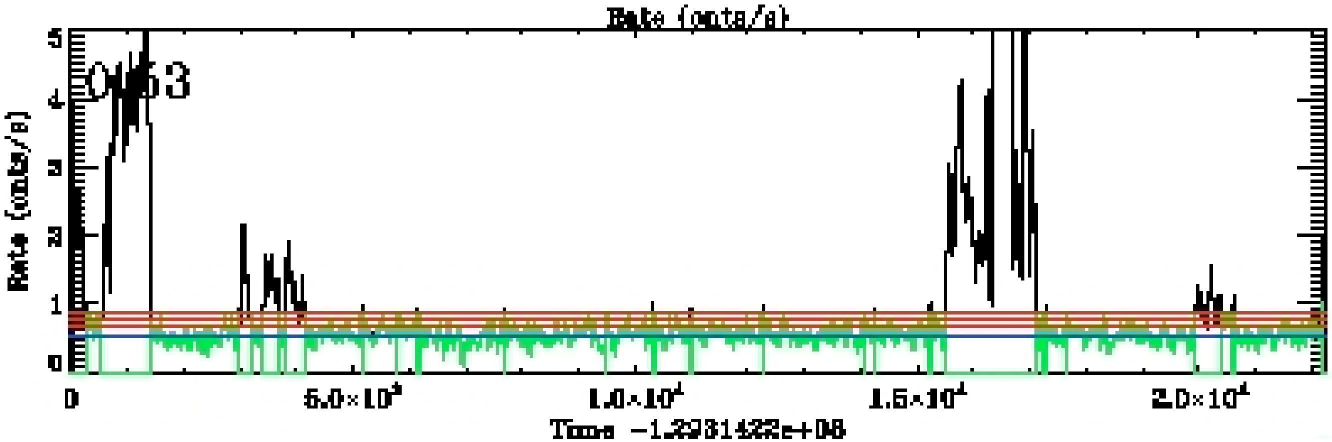
1. Extract spectrum from region of interest
2. Extract QPB spectrum from same region
   (from stowed, FWC, or dark-earth data)
3. Apply corrections for time variability
4. Normalize at high energies

- For image analysis

1. Determine strength from spectra for band-pass
2. Scale the QPB images

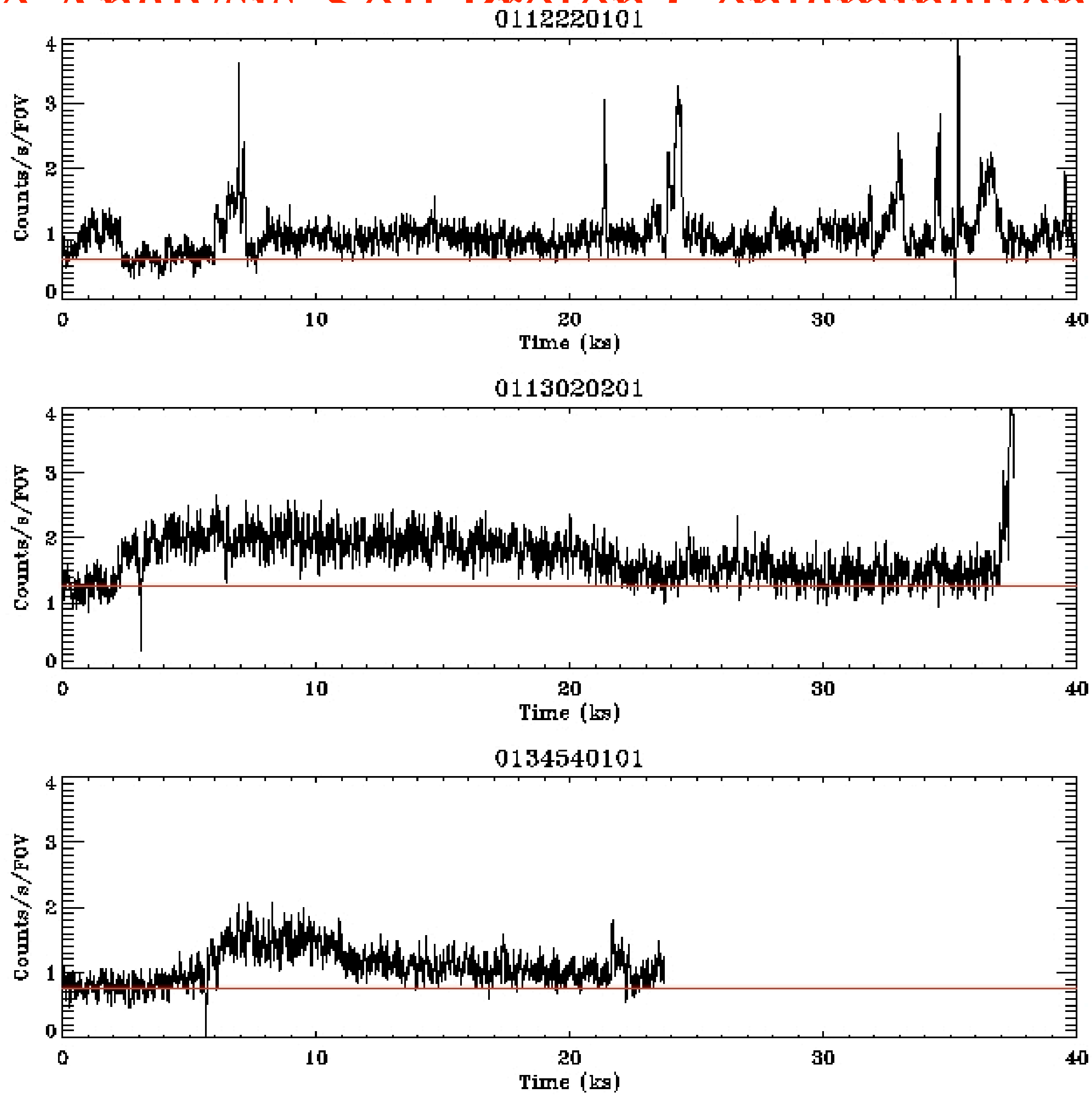
Diffuse Analysis-Soft Proton Contamination

- SPC is better known as “background flares”
  - Due to MeV protons focused by telescope mirrors
- Effects Chandra and XMM, not Suzaku or ROSAT
- Mitigated by light-curve cleaning – but there is residual



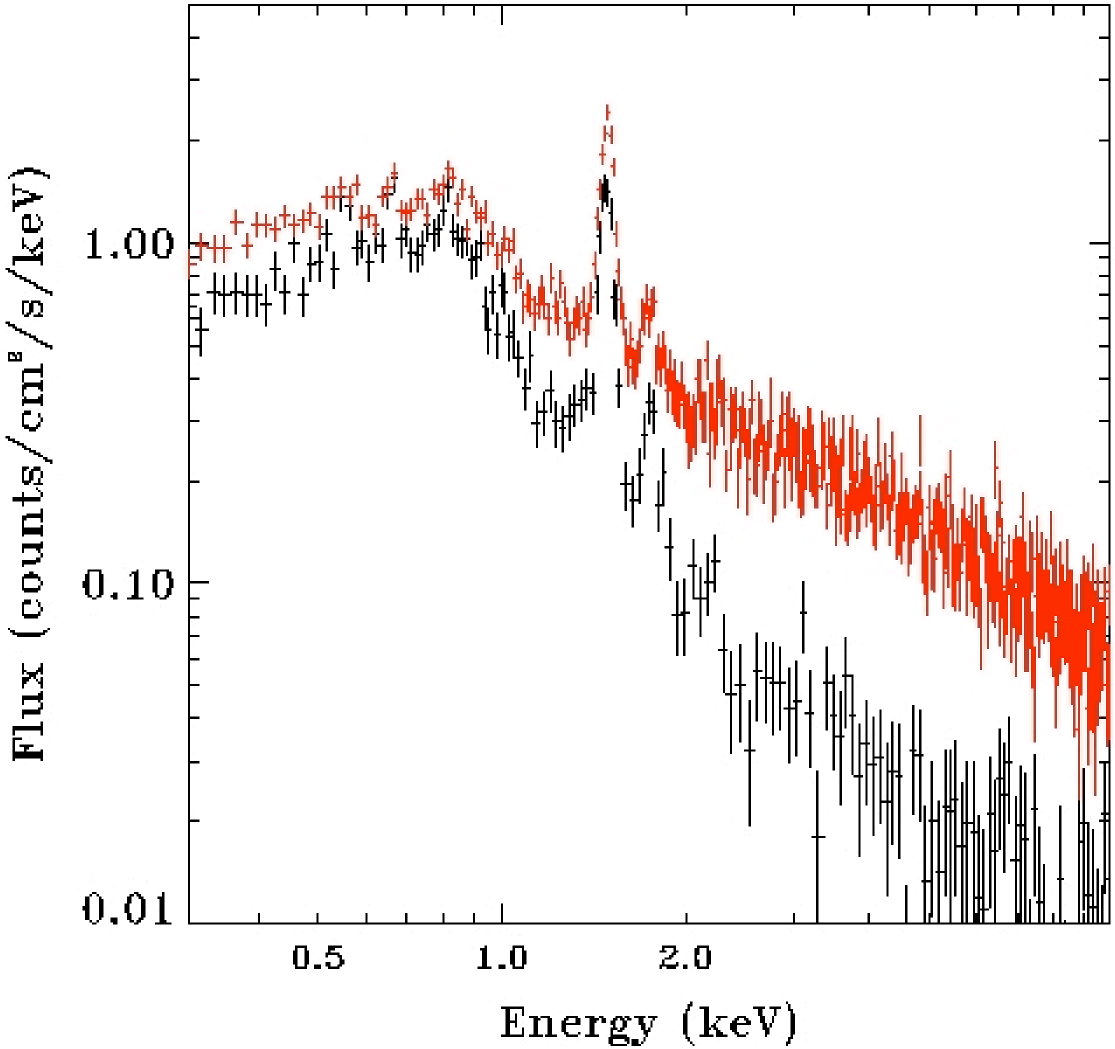
Diffuse Analysis Soft Proton Contamination

- SPC
  - D
- Effe
- Miti   dual



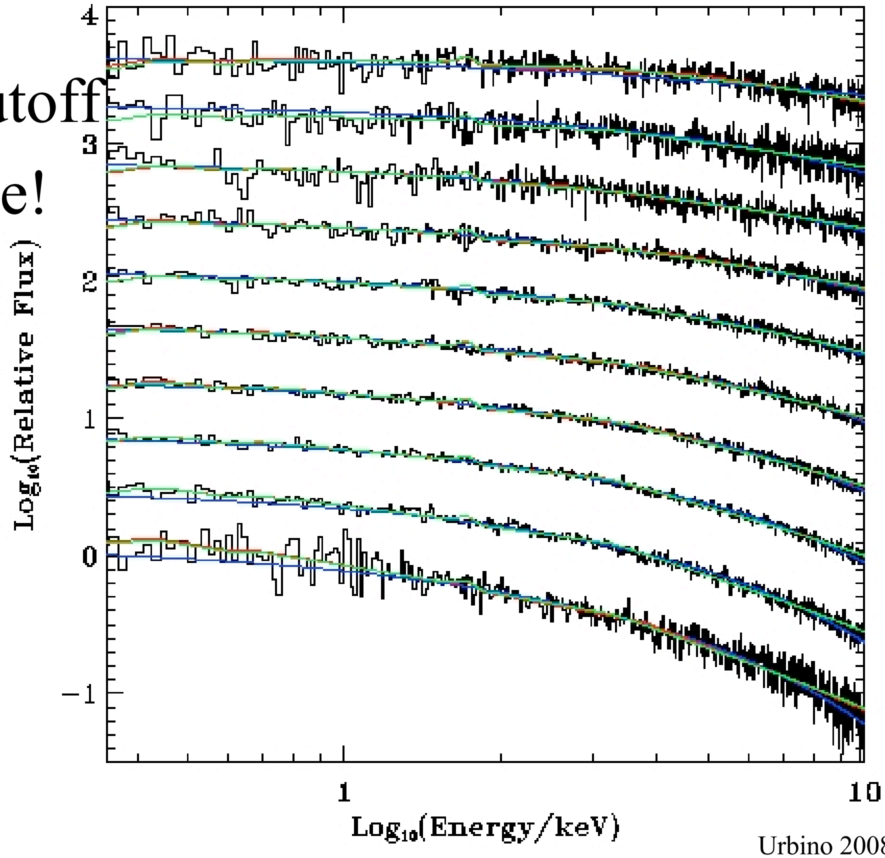
Diffuse Analysis-Soft Proton Contamination

- Usually noticeable as smooth excess at E>3 keV



Diffuse Analysis-Soft Proton Contamination

- Usually noticeable as smooth excess at E>3 keV
- The exact spectral shape depends on the observation
- Usually fit well by:
  - Broken power law
  - Power law with exponential cutoff
  - Fit without instrument response!



Diffuse Analysis-Soft Proton Contamination

- Usually noticeable as smooth excess at E>3 keV
- The exact spectral shape depends on the observation
- Usually fit well by:
  - Broken power law
  - Power law with exponential cutoff
  - Fit without instrument response!
- Spatial distribution is *not* like the photon distribution
  - Well determined for XMM, poorly for Chandra

Diffuse Analysis-Soft Proton Contamination

- Usually noticeable as smooth excess at E>3 keV
- The exact spectral shape depends on the observation
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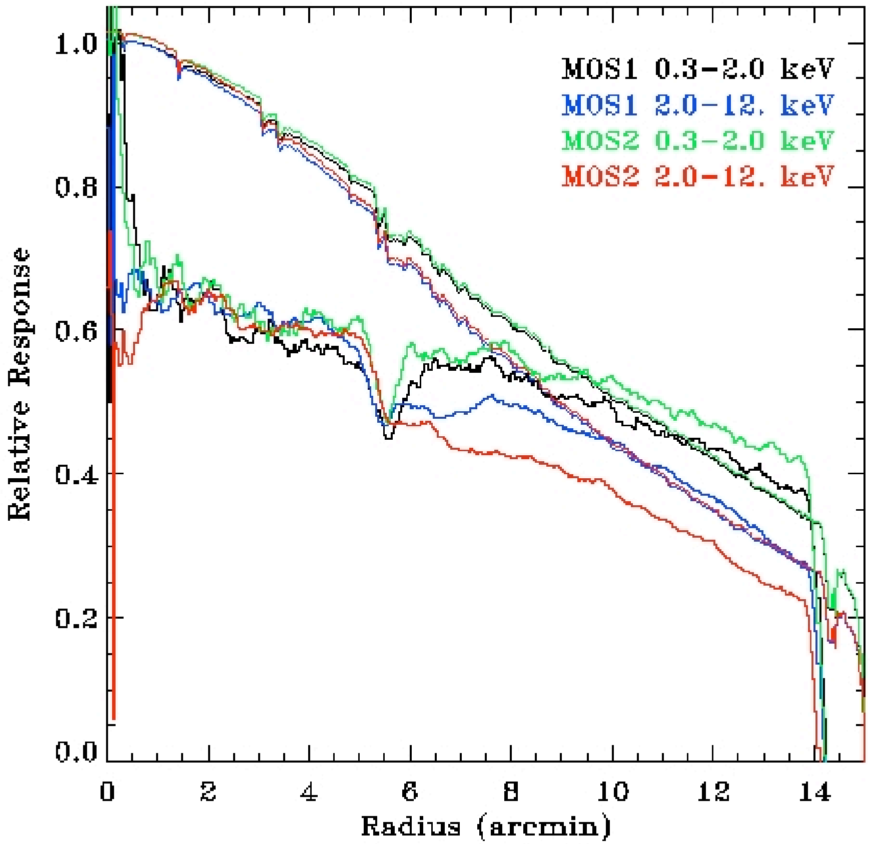


Diffuse Analysis-Soft Proton Contamination

- Technique

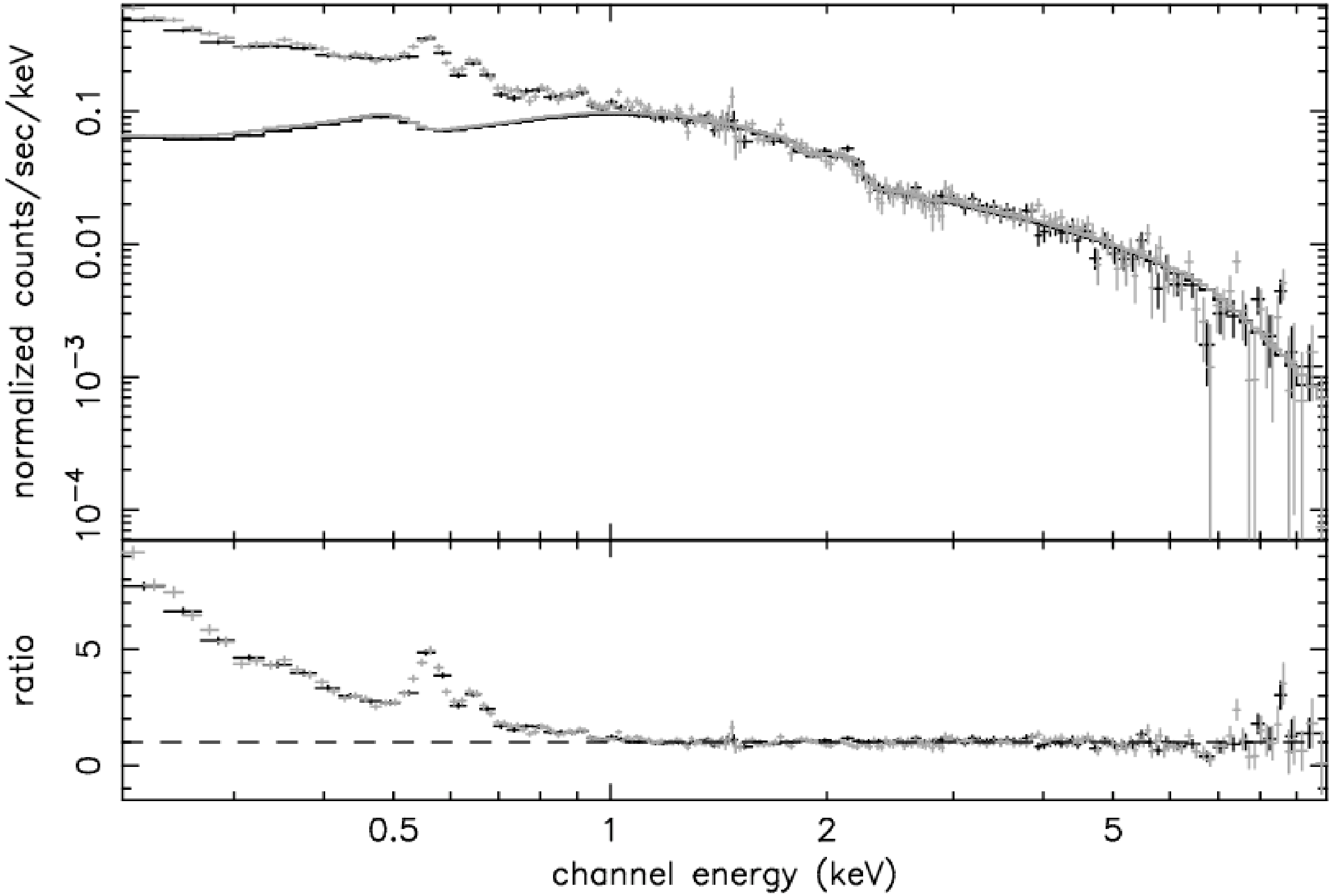
1. Clean the light-curve to remove obvious contamination
2. Fit the spectrum with all known components
3. If there is a smooth high energy excess

   Add a component with the correct spectral shape

   Fit without the instrument response or redistribution matrix

Diffuse Analysis-Background-Unresolved AGN

- Spectral shape of unresolved AGN extensively studied
- Typically modeled as a power law with _=1.42-1.46

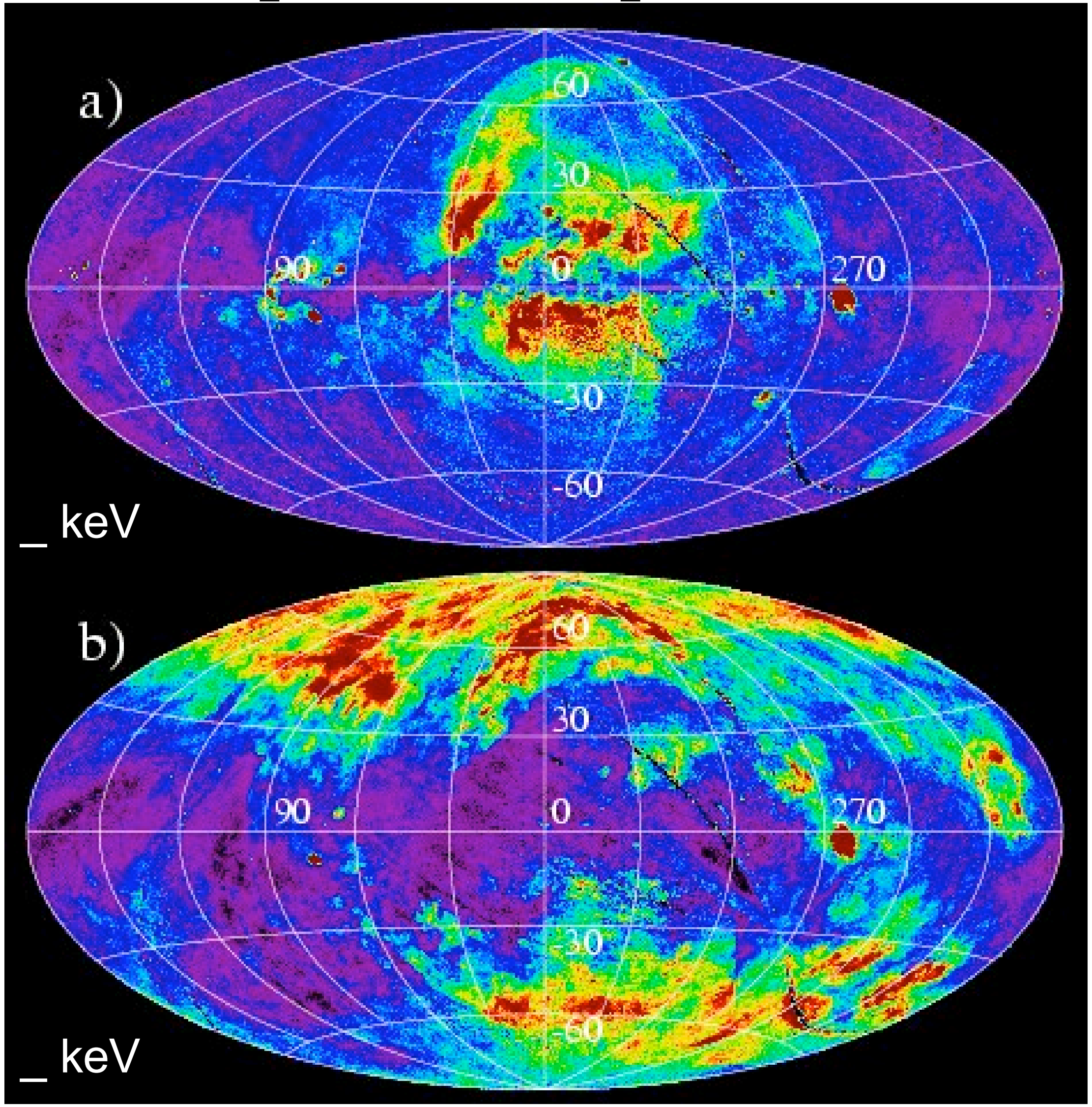


Diffuse Analysis-Background-Unresolved AGN

- Spectral shape of unresolved AGN extensively studied
- Typically modeled as a power law with _=1.42-1.46
- Normalization 9.5-10.5 keV/cm2/s/sr/keV
  - Depends upon point source removal limit
- Uncertainties
  - Behavior at E<1 keV poorly understood
  - Spectral shape may differ in very deep observations
- Memo: your source may absorb this component

Diffuse Analysis-Background-Galactic Emission

- Strength and spectral shape varies with position



Diffuse Analysis-Background-Galactic Emission

- Strength and spectral shape varies with position
- DO NOT USE MEAN SKY BACKGROUNDS
  - At least not below 2 keV
  - Use a local measure instead
  - Very important because galaxies and the soft components of clusters of galaxies have spectra similar to that of our own Milky Way
- IF
  - The RASS and N(H) maps have similar values for your source region and your background region AND
  - The two regions are a few degrees apart
- THEN
  - spectral shape is likely similar, but the strength of the emission is not

Diffuse Analysis-Background-Galactic Emission

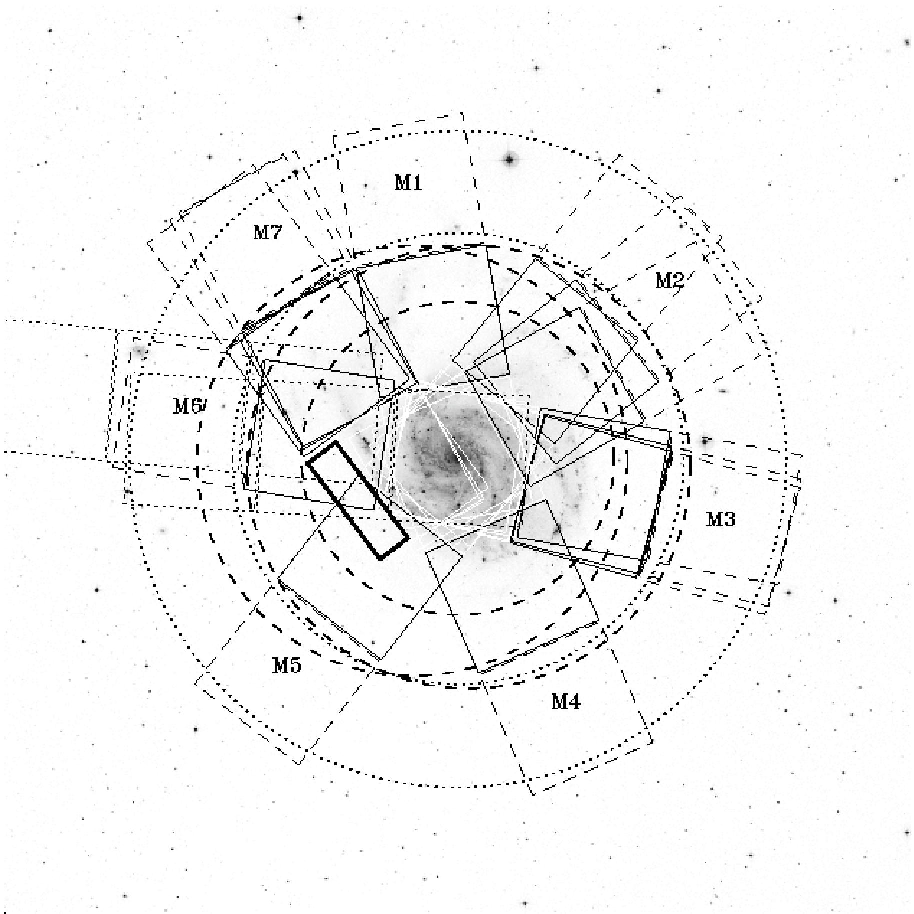
- Technique

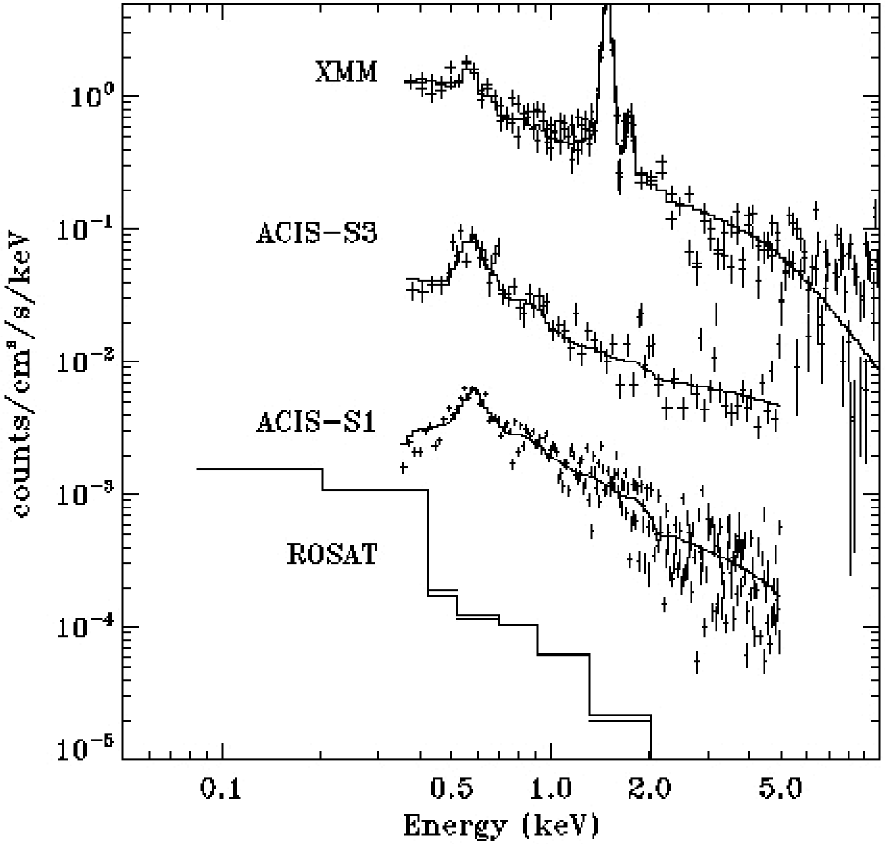
1. Extract source spectrum
2. Extract nearby "background" spectrum
3. Fit background spectrum with

   $APEC_L$+wabs($APEC_D$+$APEC_D$+pow)

   kT_L~0.09 keV, kT_D~(0.25,0.1)

   (see Kuntz & Snowden 2000)
4. Constrain fit with RASS data
5. Apply fit to source spectrum, allowing thermal normalizations to vary

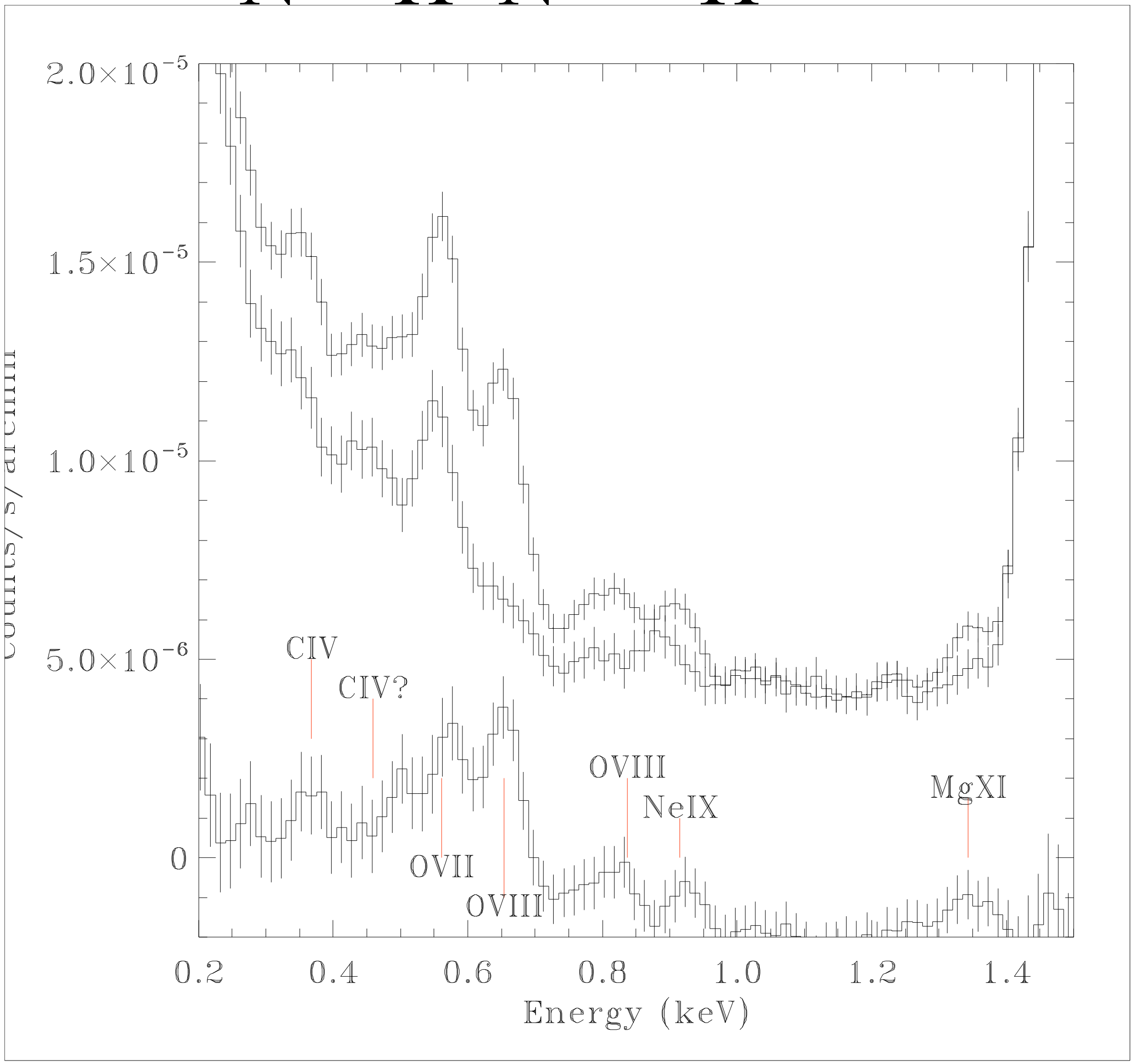

M1
M7
M2
M6
M3
M5
M4


XMM
ACIS-S3
ACIS-S1
ROSAT
counts/cm²/s/keV
Energy (keV)
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0.1
0.5
1.0
2.0
5.0

Diffuse Analysis-Background-SWCX

Solar Wind Charge Exchange Emission (SWCX)

$N^{+i} + H \; N^{+i-1} + H^{+} +$



Diffuse Analysis-Background-SWCX

Solar Wind Charge Exchange Emission (SWCX)

$$N^{+i}+H\_N^{+i-1}+H^{+}+\_$$

Sources

- Neutral ISM flowing through solar system
  - Strong spatial dependence
- Neutral material in earth's extended atmosphere
  - Strong time variability
- Since composition of solar wind varies

  _spectral shape varies strongly
- Responsible for erroneous discovery of soft component in the Coma cluster

Diffuse Analysis-Background-SWCX

Technique

- Currently none (though see Carter & Read 2009)
- If there are multiple observations, comparison may reveal problems
- Active work at CNRS and GSFC

Diffuse Analysis-Summary

Getting your backgrounds right is crucial for the study of galaxies, groups of galaxies, clusters of galaxies, and the hot ISM of the Milky Way

Technique

1. Create light-curve and clean to remove most SPC
2. Create and normalize QPB spectrum
3. Extract "blank sky" spectrum and fit Galactic emission and unresolved AGN spectrum
4. Extract source spectrum, subtract QPB spectrum, fit: source + (Galactic+XRB) + SPC

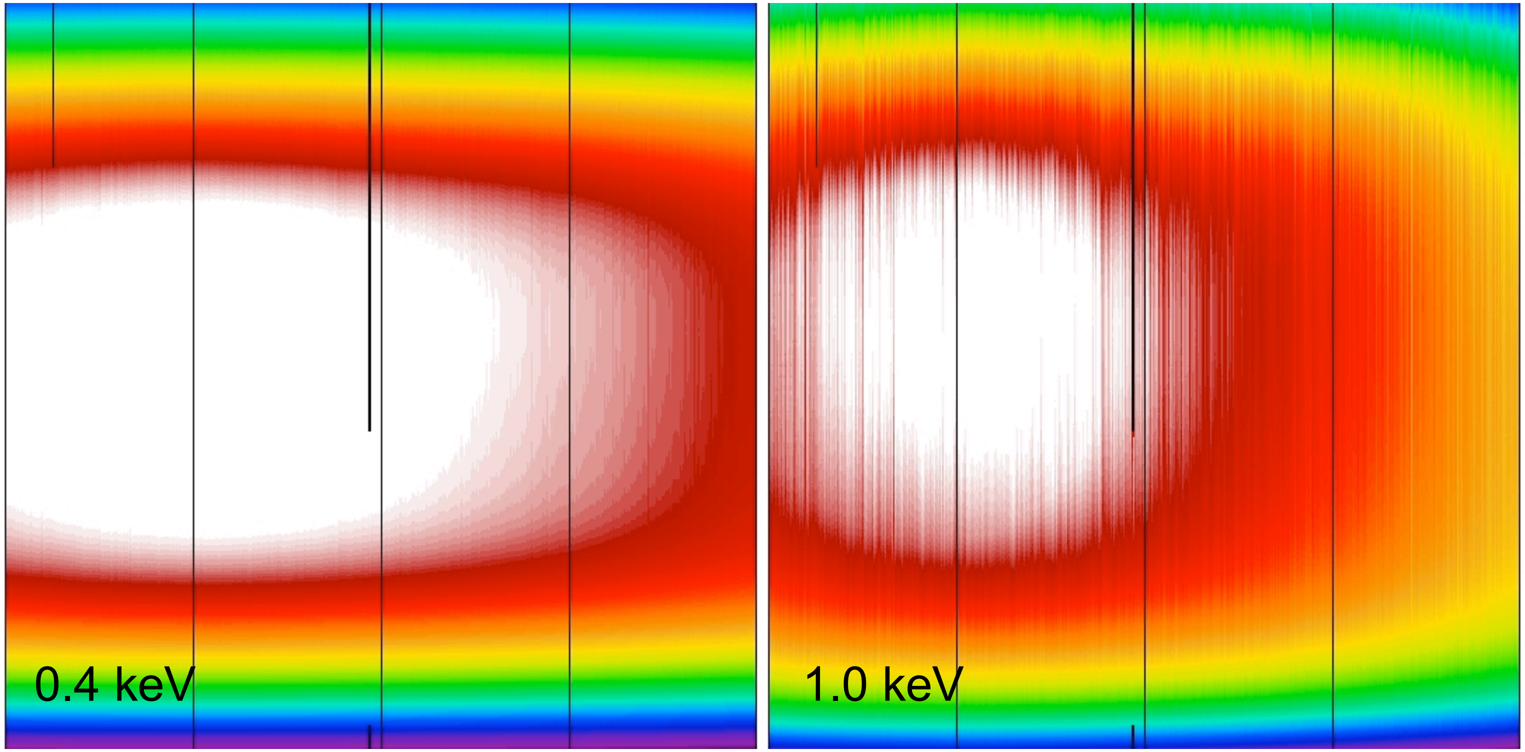
Diffuse Analysis-Imaging

(Counts-Backgrounds)/(Exposure time_Eff. Area Map)

Since effective area map is energy dependent –

correct map requires knowledge of source spectrum.

Application of monochromatic map _ spurious features



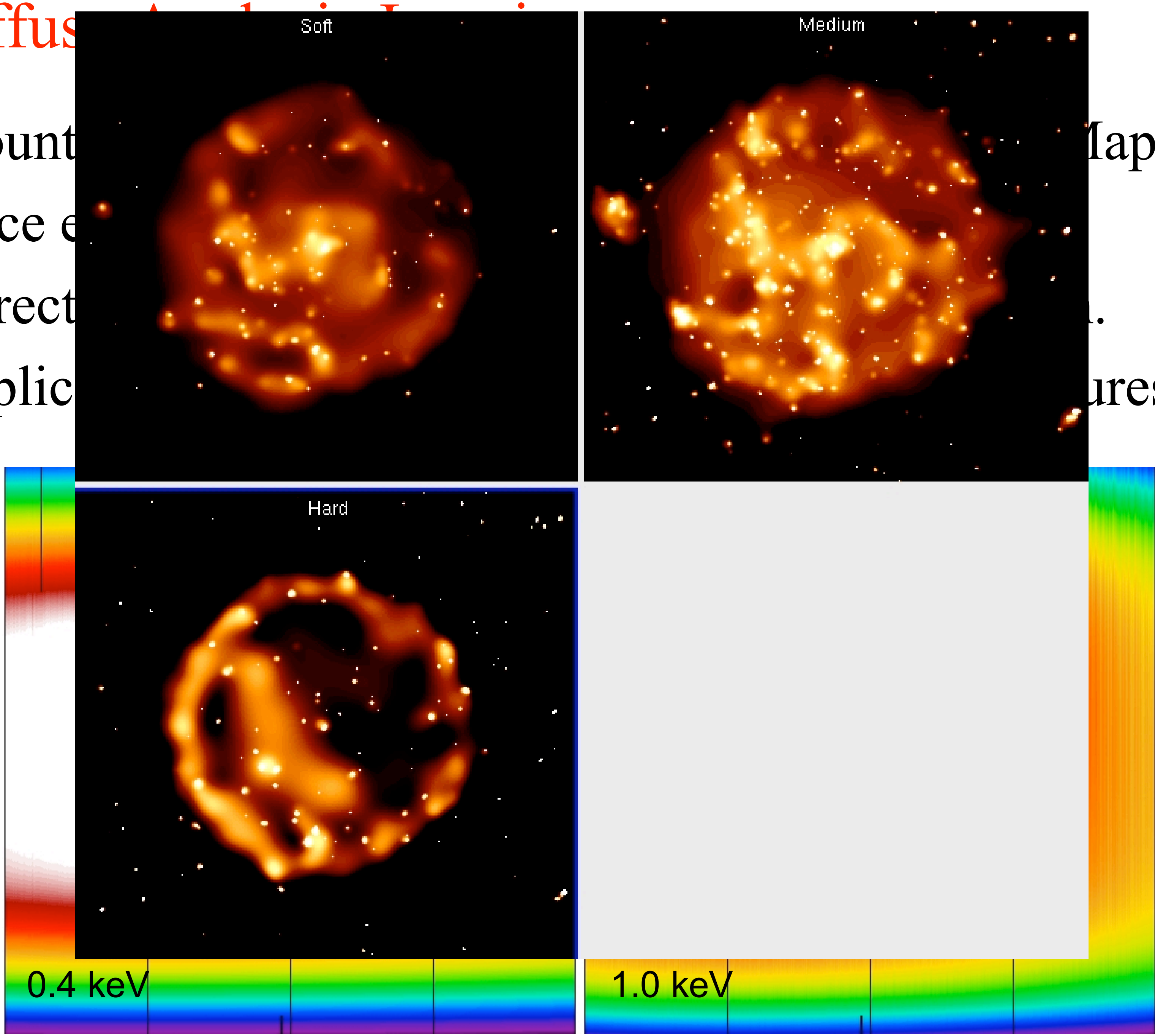
Diffus

(Count … Map)

Since e …

correct … .

Applic … ures



Diffuse Analysis-Tools

Chandra – CIAO provides standard tools (spectral extraction, etc.), CXC provides background data and some tools for applying backgrounds

XMM – BGWG provides robust tools for calculating backgrounds: XMM-ESAS (XMM site or HEASARC)

Suzaku – fewer backgrounds, fewer problems, less need for tools, use HEASoft

ROSAT – robust tool set developed at MPE & GSFC available through the HEASARC

Diffuse Analysis-Tools

Mosaicking: putting together many exposures

- Chandra – merge script (limited application)
- XMM – use XMM-ESAS (from HEASARC)
- ROSAT – use ESAS (from HEASARC)

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