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Why High Energy Data Are Different

A View From *Chandra*

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IVOA Interop

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Well, Why?

High energy photon

Optical/IR/radio photon

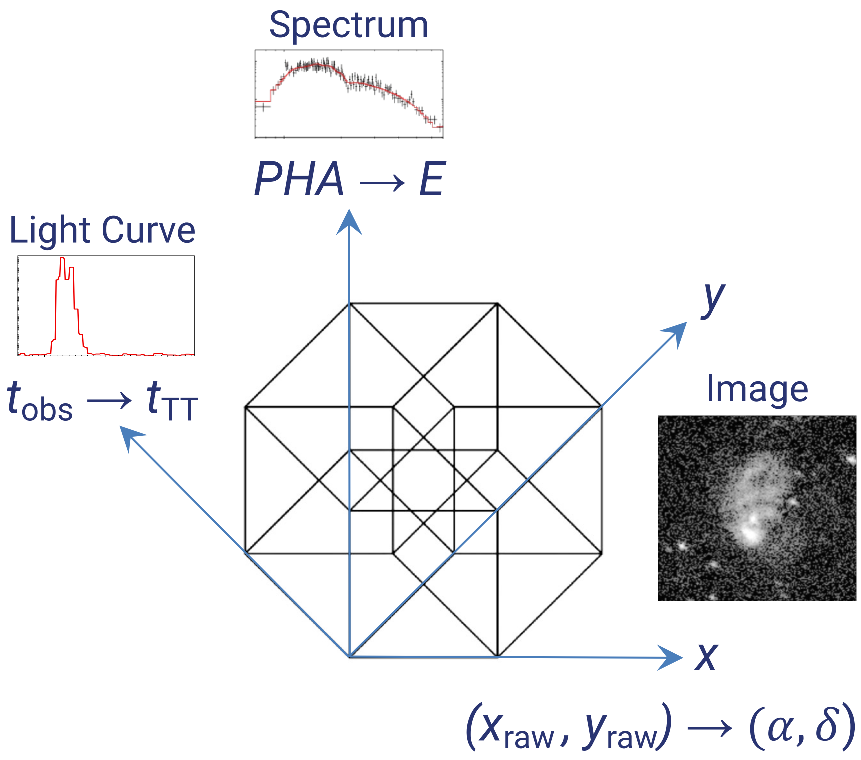
The X-ray Data Hypercube

- *Chandra* detects *individual X-ray photons* with energies ~0.1–10.0 keV ⇒ photon counting

- Each X-ray *event* records a (typically) 4-D set of observables that map to actual photon properties
  - Detector location $(x_{raw}, y_{raw}) \rightarrow$ Sky position (α, δ)
  - Spacecraft time $t_{obs} \rightarrow$ Photon arrival time t_{TT}
  - Pulse height *PHA* → Photon energy *E*

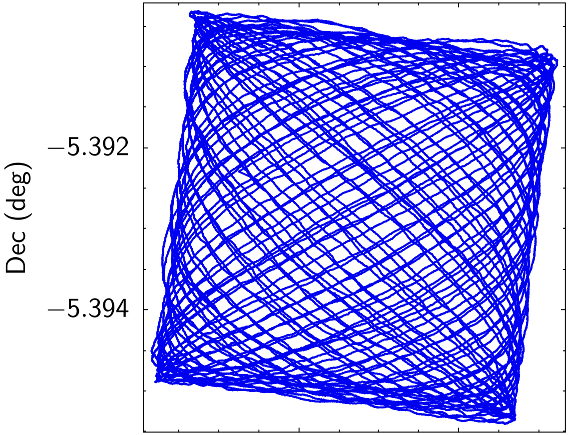
- A set of X-ray events (*e.g.*, from a single observation) is termed an *event list*

- *Chandra* can reliably detect sources with as few as ~4–5 counts ⇒ Poisson regime



Chandra-Specific Considerations

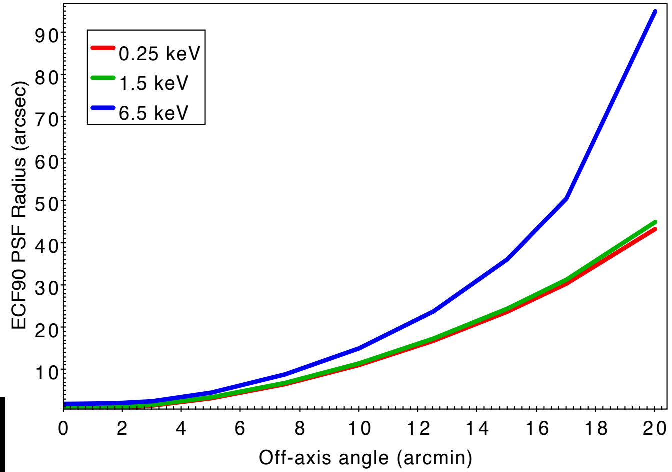
- Telescope pointing *dithers on the sky*
  ⇒ Source samples different regions of the detector with different calibrations during the exposure

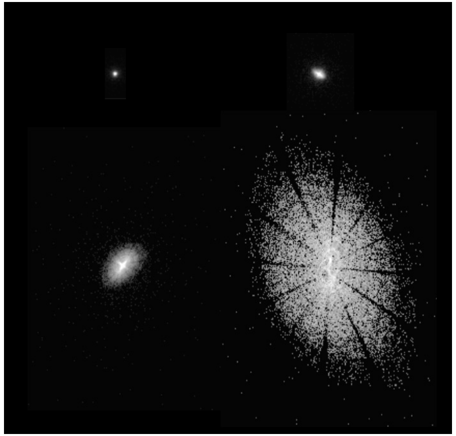


Above: Aspect solution (RA, Dec) vs. time corrects for dither motion of source on detector

- PSF varies with *energy* and *position within FoV*
  ⇒ PSF depends on (unknown) source spectrum

Right: 90% Encircled Counts Fraction PSF radius vs. off-axis angle for 3 energies





Left: Chandra PSF *for a specific energy* on-axis, and 4, 8, 18 arcmin off-axis (log scale, various azimuthal angles)

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X-ray Pulse Height Spectroscopy

- The expected observed channel distribution of detected source counts $M(E', \hat{p}', t)$ is:

What we observe | What we want

$$\boxed{M(E', \hat{p}', t)} = \int dE\, d\hat{p}\, R(E'; E, \hat{p}, t)\, P(\hat{p}'; E, \hat{p}, t)\, A(E, \hat{p}', t)\, \boxed{S(E, \hat{p}, t)}$$

$S(E, \hat{p}, t)$ is the physical model that describes the physical energy spectrum, spatial morphology, and temporal variability of the source

$R(E'; E, \hat{p}, t)$ is the *redistribution matrix* that defines the probability that a photon with actual energy E, location $\hat{p}$, and arrival time t will be observed with apparent energy E' and location $\hat{p}'$

$A(E, \hat{p}', t)$ is the instrumental *effective area* (sensitivity)

$P(\hat{p}'; E, \hat{p}, t)$ is the photon spatial dispersion transfer function (the instrumental PSF)

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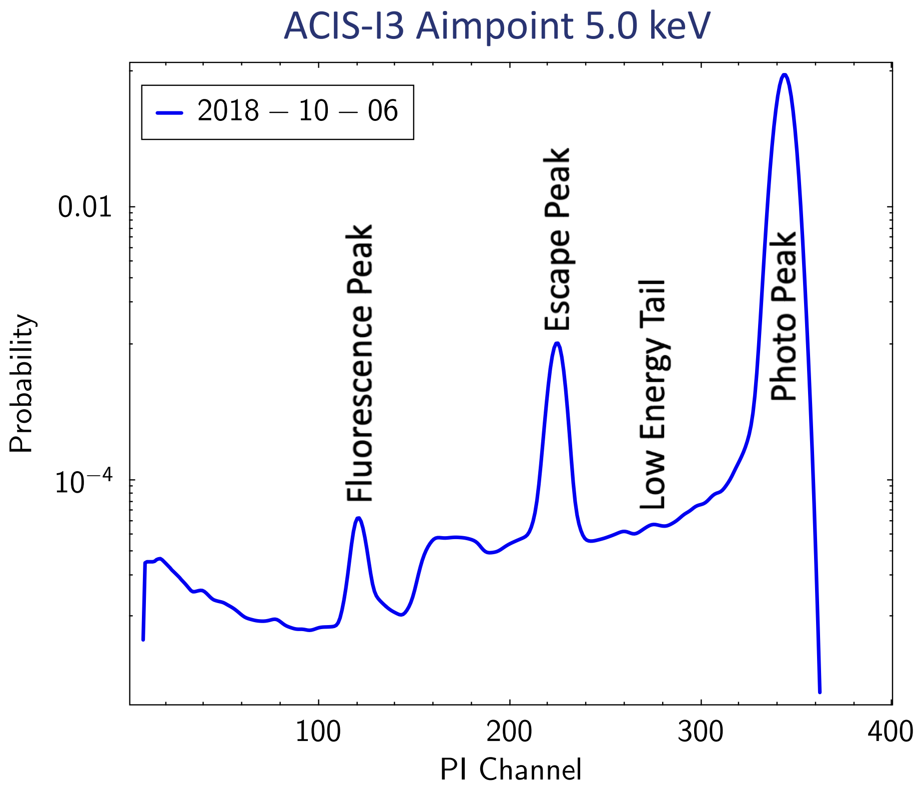
X-ray Pulse Height Spectroscopy — “Line Spread Function”

- X-ray photons of a given energy may be recorded in different detector channels with varying probabilities due to interactions with the telescope and detector optics
- Analogous to the line spread function in optical astronomy
- For *Chandra*, this response varies with *location on the detector* and *observation epoch*



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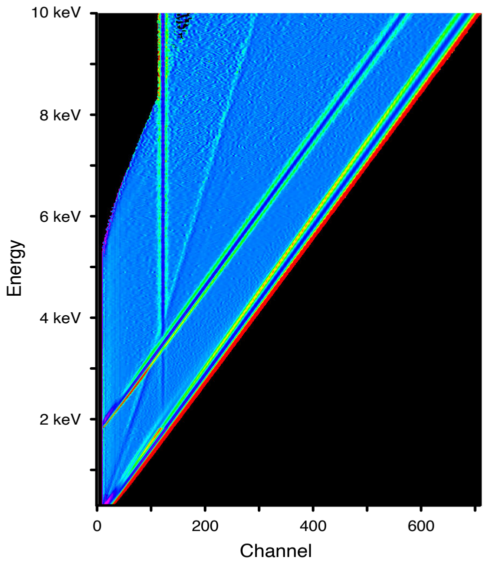
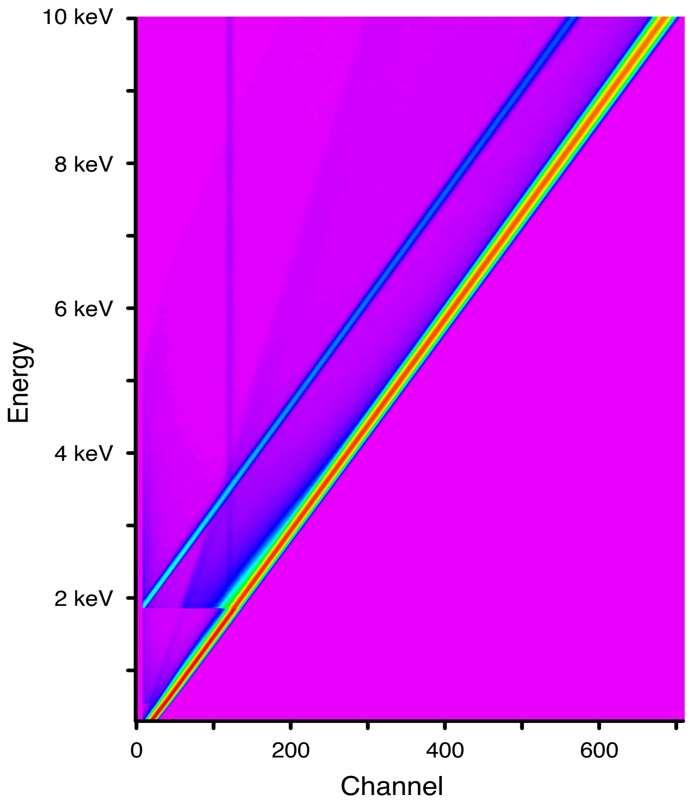
Redistribution Matrix

- The redistribution matrix $R(E'; E, \hat{p}, t)$ maps the relationship between the incident photon energy and the detected signal distribution over detector channels (i.e., the event pulse height)
  - *Chandra* uses the NASA HEASARC OGIP-standard RMF (Redistribution Matrix File) FITS file format

Right: Example variation of the RMF across the *Chandra* dither pattern



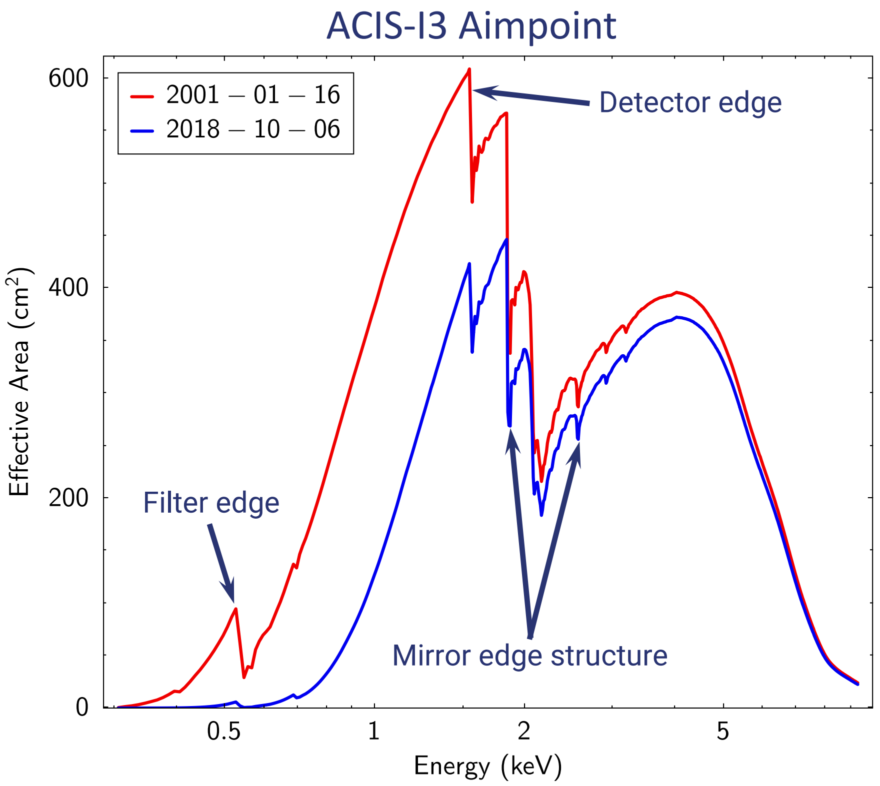


X-ray Pulse Height Spectroscopy — "Sensitivity"

- The *ancillary response* $A(E, \hat{p}', t)$ records the effective area of the telescope/detector combination
  - *Chandra* uses the NASA HEASARC OGIP-standard ARF (Ancillary Response File) FITS file format

- Analogous to the sensitivity curve in optical astronomy

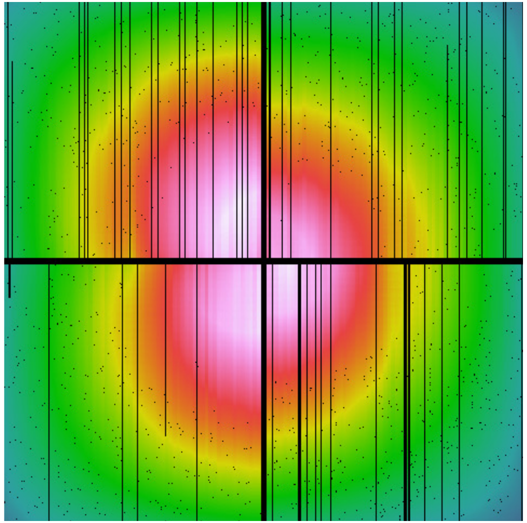
- Includes geometric collecting area × optics, gratings, detector efficiencies



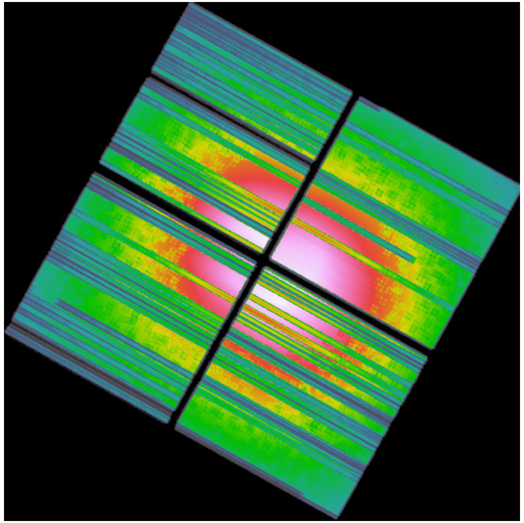
How Does The Response Vary Over The Field?

- *Chandra* instrument & exposure maps
  - Vary with location because of vignetting and detector non-uniformities
  - Vary with observation epoch
  - Depend on energy

⇒ Maps integrated over energy depend on source spectrum



Instrument map records the instrument sensitivity in detector coordinates



Exposure map is the instrument map convolved with the aspect solution

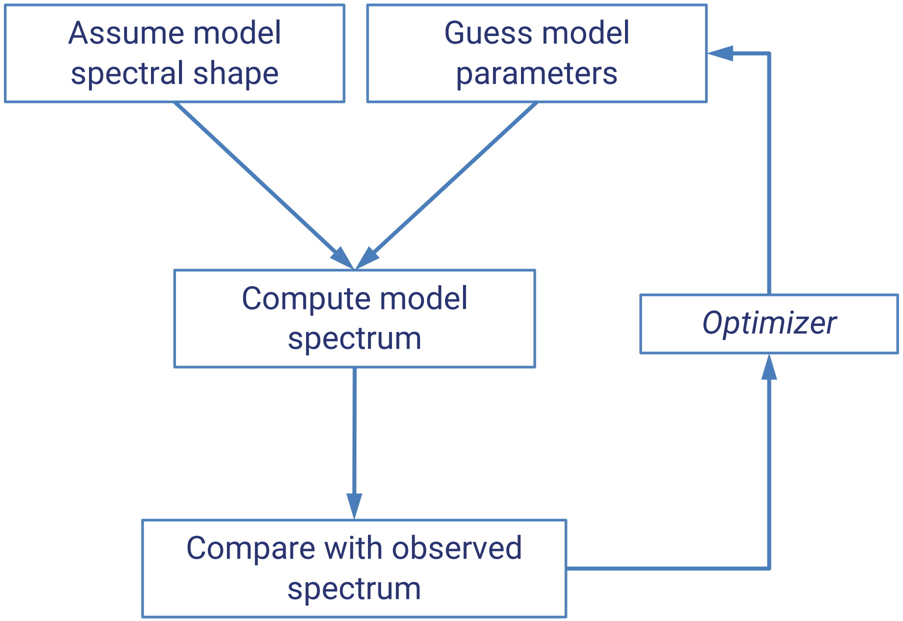
Figures from CXC guide “An X-ray Data Primer — What I Wish I Knew when Starting X-Ray Astronomy”

Solving For The Source Model Parameters

- *The transformation between* $S(E, \hat{p}, t)$ *and* $M(E', \hat{p}', t)$ *is not easily invertible*

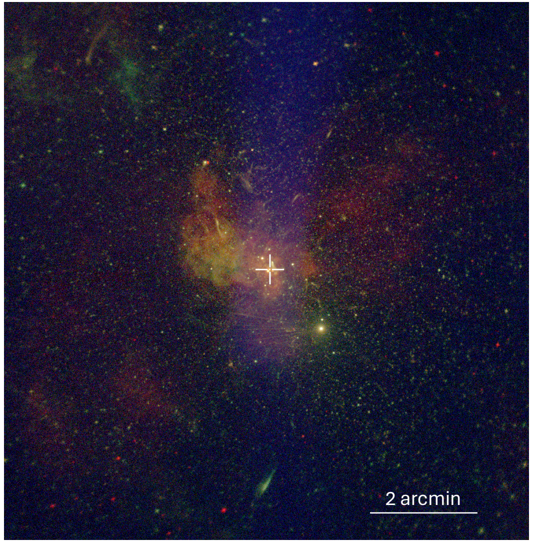
- *Forward fitting*
  - Propose a model for $S(E, \hat{p}, t)$
  - Fold the model through the responses
  - *Optimize* the parameters of $S(E, \hat{p}, t)$ by comparing with the observed channel counts distribution

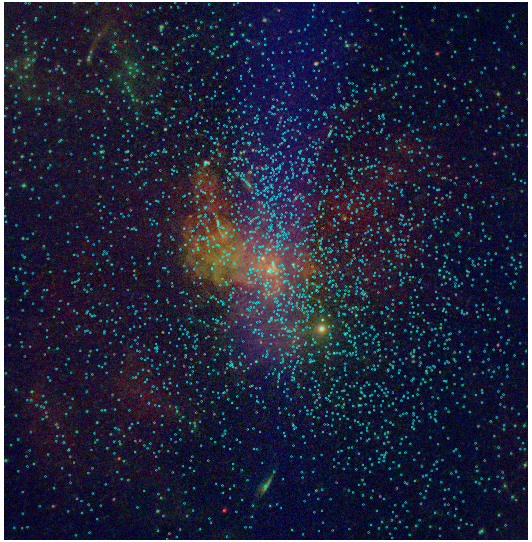
Forward Fitting



Chandra Source Catalog Release 2.1

- Source positions, extents, multi-band aperture photometry, temporal variability, hardness ratios, spectral fits
- All measurements have associated confidence intervals
- Imaging data released publicly through 2021
- Stacked observations for fainter detections
- Tied to Gaia-CRF3 astrometric frame
- IVOA compliant interfaces
- ~408K unique X-ray sources on the sky
- ~2.1M detections and photometric upper limits
- ~730 square degrees on the sky
- ~45TB science ready FITS format data products





A cutout of a roughly 3 Ms observation stack (a co-add of 86 observations) from CSC 2.1, centered on Sgr A* (identified by the cross). The positions of roughly 3,300 X-ray point sources in this region from CSC 2.1 are identified.

For more information see
https://cxc.cfa.harvard.edu/csc/

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Chandra Source Catalog X-ray Property Measurements

Measurements are only meaningful if we understand the measurement confidence

- *Optimization methods and Bayesian inference* are used extensively for X-ray data analysis

  ⇒ Measurements may be represented in ways that are less commonly used in other wavebands

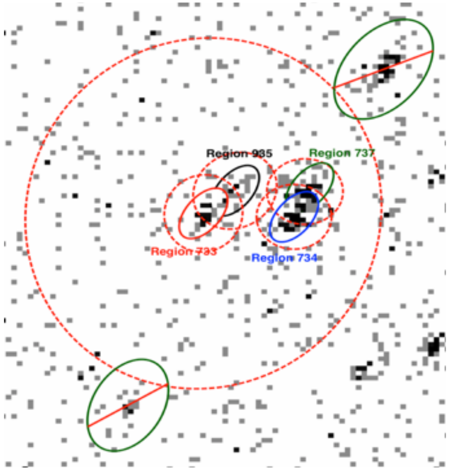
- *Example:* Bayesian X-ray aperture photometry (Primini & Kashyap 2014 ApJ 796, 24)
  - Solve for multiple detections/overlapping apertures and background simultaneously
  - Compute joint posterior probability density function (JPDF) for source and background fluxes

$$P(\mu_{s_1}...\mu_{s_n}, \mu_b | C_1...C_n, B) = K P(\mu_b) \mathrm{Pois}(B|\mu_b) \prod_{i=1}^{n} P(\mu_{s_i}) \mathrm{Pois}(C_i|\mu_{s_i})$$

  - Calculating *marginalized posterior probability density function (MPDF)* for a single source by integrating the JPDF is computationally complex

$$P(s_i|C_1...C_n, B) = \int_{b, s_j \neq s_i} \cdots \int db \left(\prod_{j \neq i} ds_j \right) P(\mu_{s_1}...\mu_{s_n}, b | C_1...C_n, B)$$

  ⇒ Optimize using Markov chain Monte Carlo sampler



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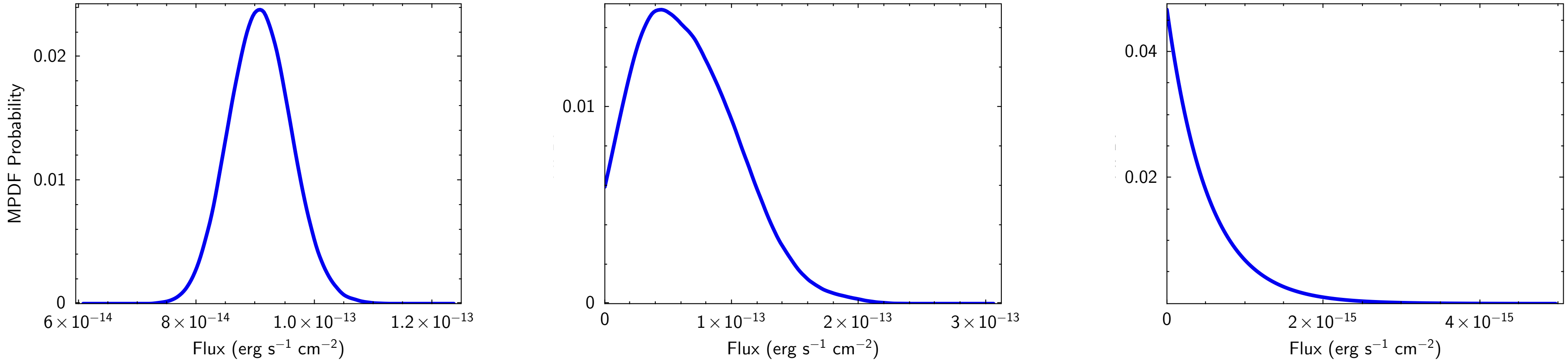
Example: Bayesian X-ray Aperture Photometry

- Posteriors provide an estimate of the measurement value (*e.g.*, the mode of the distribution) and arbitrary lower and upper confidence intervals can be evaluated
  - MPDFs are unlikely to be Gaussian in the Poisson regime
  - Posteriors must be accompanied by information about models and prior probability distributions
  - Note there are many types of measurements for which multi-dimensional posteriors are appropriate



Three example X-ray photometry MPDFs for different source fluxes

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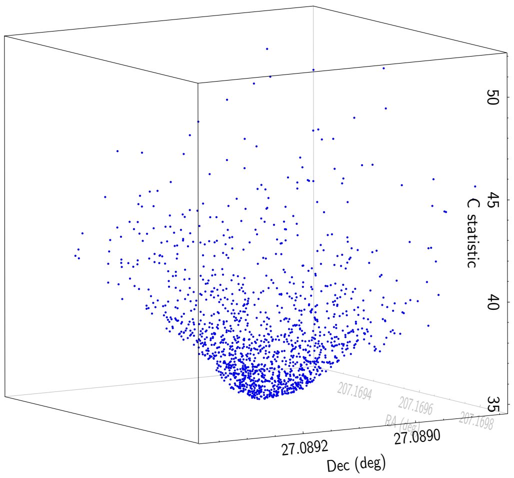
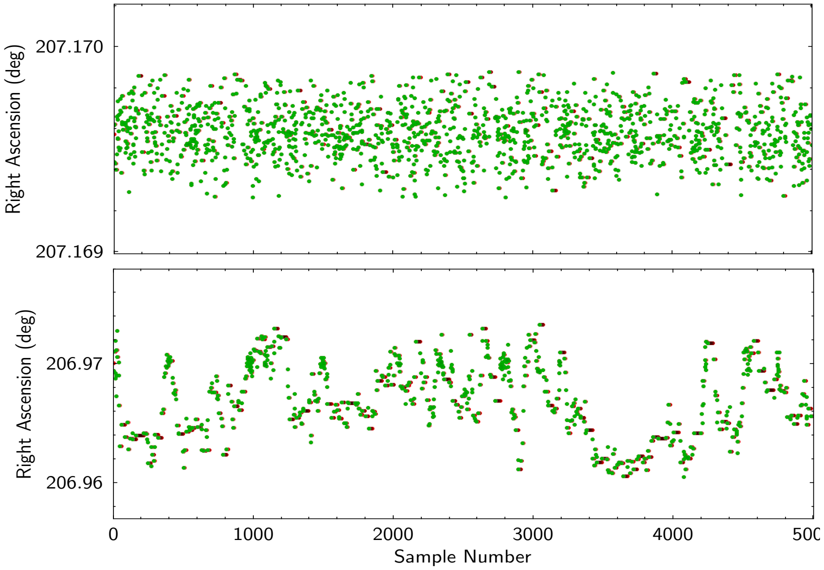
Example: Markov Chain Monte Carlo Position Confidence

- Markov chain Monte Carlo draws provide more information but are less directly interpretable
  - Mode of sample values after burn-in is the measurement value
  - Distribution of the sample values is the MPDF from which confidence intervals can be calculated
  - Convergence can be quickly evaluated visually from the distribution of samples
  - Sample subsets can be used to compute numerical convergence criterion, $\hat{R}$





Above: Position confidence MCMC draws

Right: Example converged and un-converged MCMC draws

Conclusions

- Responses (ARF, RMF, and possibly PSF, time filter) are ancillary data products that are *necessary* to understand/interpret X-ray pulse height spectroscopy measurements
  - These products depend on *user's choice* of spectral model

⇒ **Data models must be able to capture and encode these ancillary products *and* metadata**

- Many current analysis techniques used in X-ray astronomy use Bayesian analysis methods that work robustly in the Poisson regime
  - These analyses may produce MPDFs for the parameters of interest or in some cases MCMC draws

⇒ **Data models must be able to capture and encode these representations of measurements *and* associated metadata necessary for their meaningful interpretation**

- Even quoting measurement and confidence limits don't forget that the *shape of the distribution* (*e.g.*, Gaussian) and the *confidence level* (*e.g.*, 68%, 95%) must be captured for the measurement to be useful