A New Paradigm in X-ray Spectral Analysis

Deconvolving X-ray Spectra using Machine Learning

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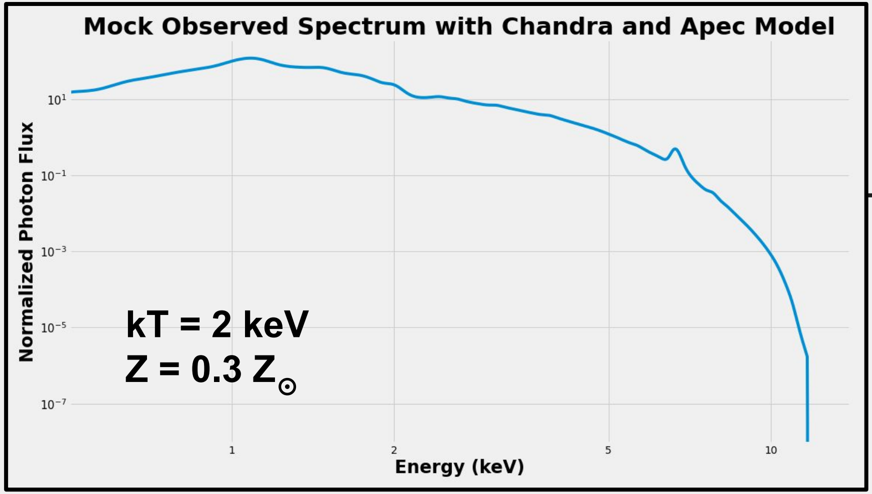
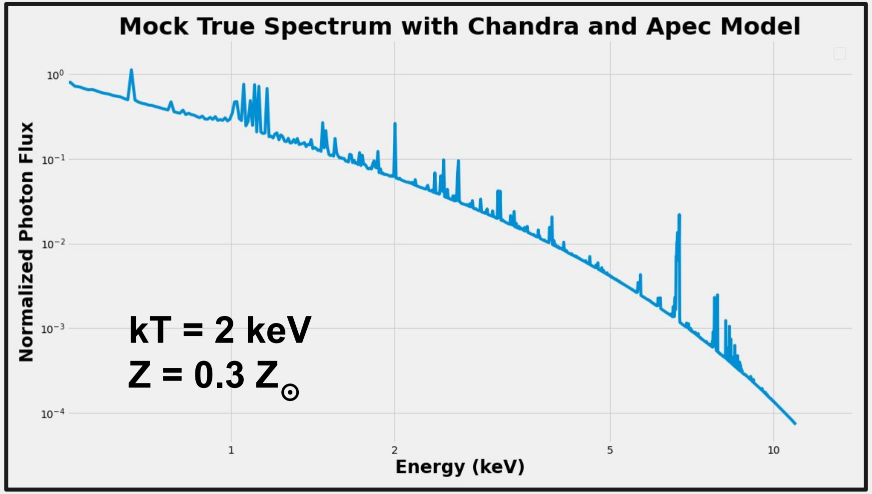
X-TRA

Observations vs Reality

What we observe

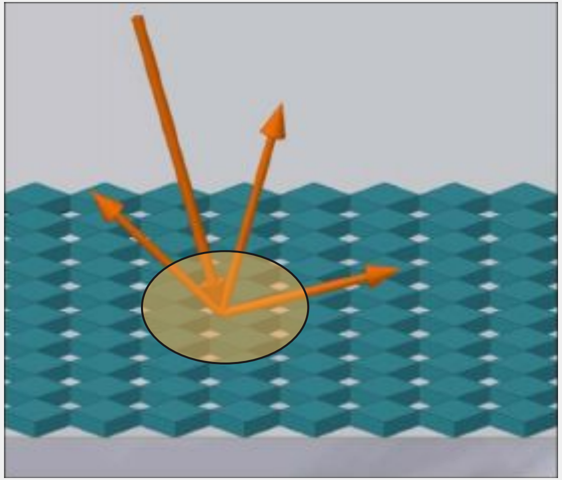


The Source's Intrinsic Spectrum

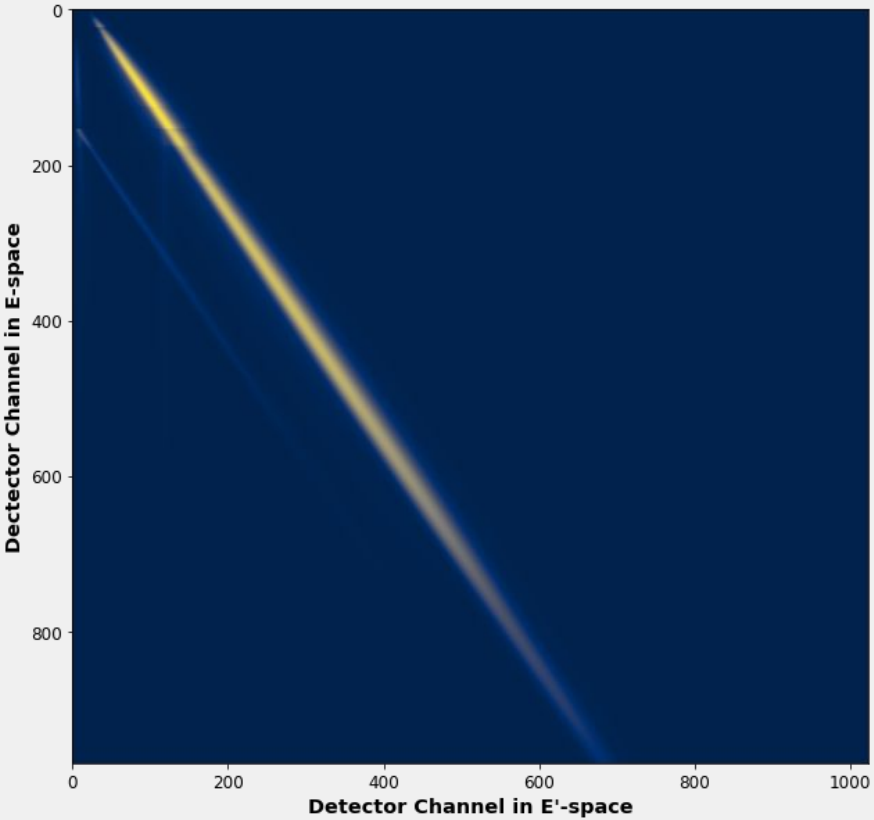


The Response Matrix

Example CCD



Example Response Matrix

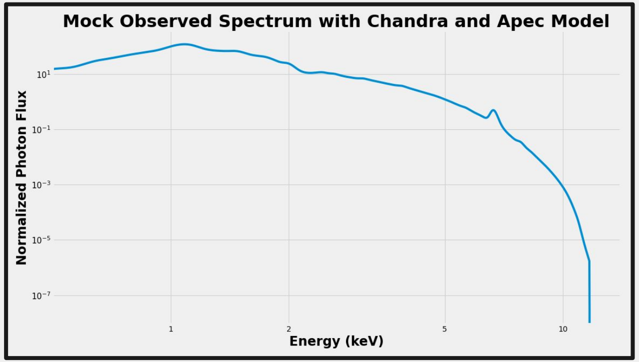


Possible Solutions for the Response Matrix

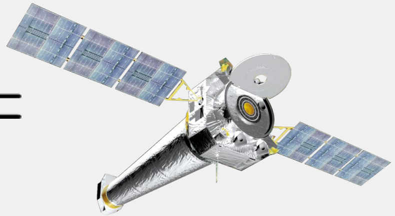
E = Photon Energy Space

E' = Detector Energy Space

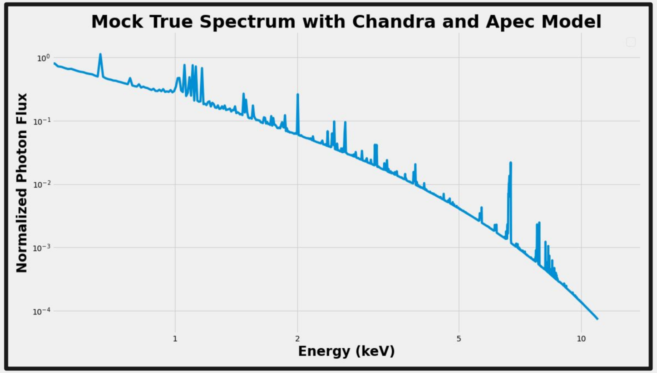
$$S_{obs}(E) = \int_0^{\infty} R(E', E)\, S_{true}(E)\; dE$$



$=$



$\otimes$



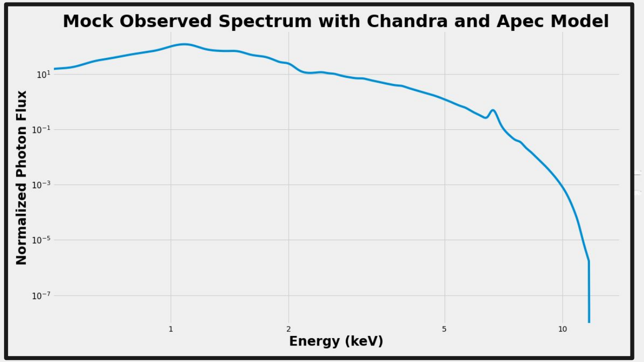
Kaastra & Bleeker 2016 ApJ

Possible Solutions for the Response Matrix

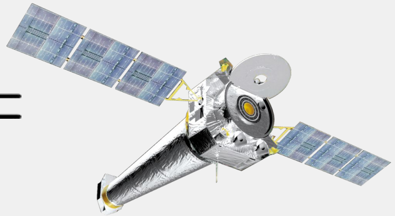
i = Photon Energy Space

j = Detector Energy Space

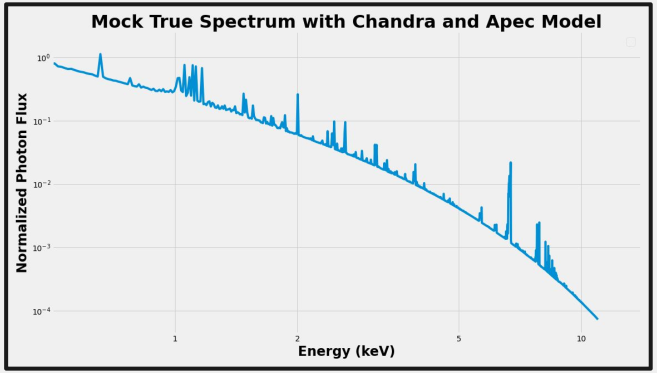
$$S_{obs_i} = \sum_{ij} R_{ij} S_{true_j}$$



$=$



$\otimes$

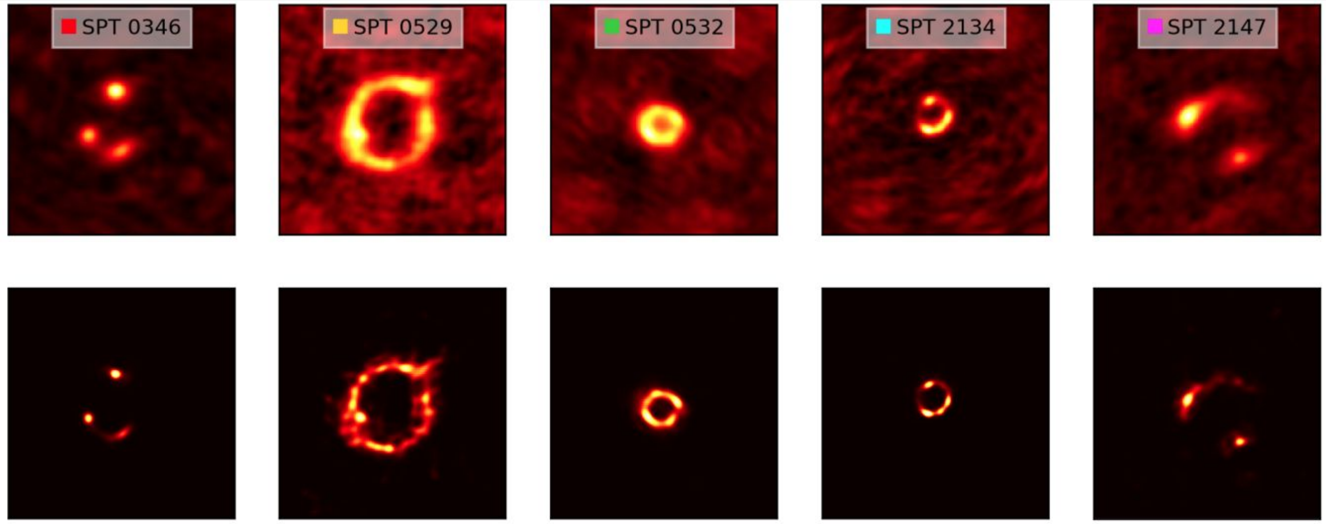


Kaastra & Bleeker 2016 ApJ; see also Rhea et al. 2021 RNAAS

Recurrent Inference Machines

How does a Recurrent Inference Machine work:

*Solves the linear equation **Ax=b** iteratively by using an **neural network** to update a solution.*

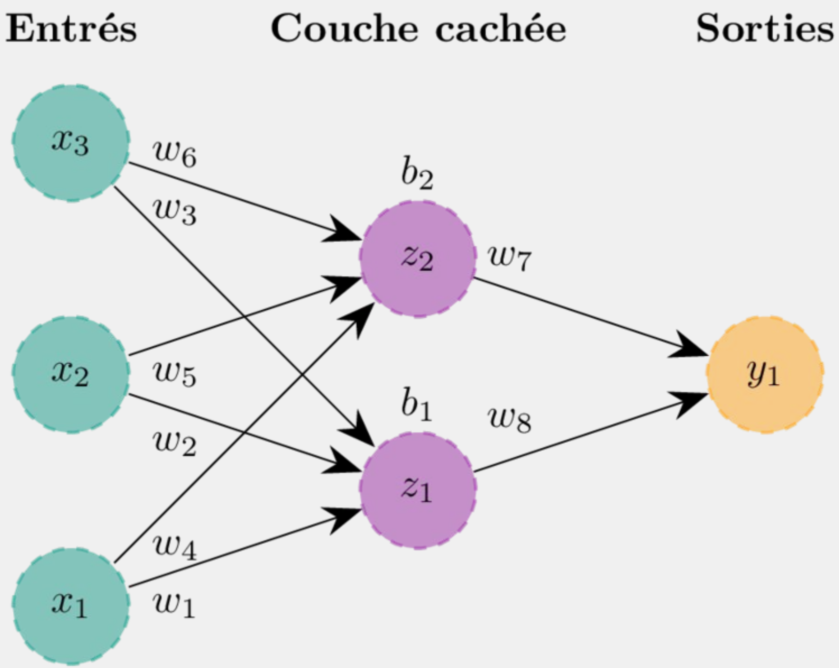


ALMA Dirty Image

RIM Deconvolved Image

Putzky & Welling 2017; arxiv.org/abs/1706.04008
Morningstar et al. 2018; arxiv.org/abs/1808.00011
Morningstar et al. 2019; arxiv.org/pdf/1901.01359.pdf

Rapid Detour: Neural Networks

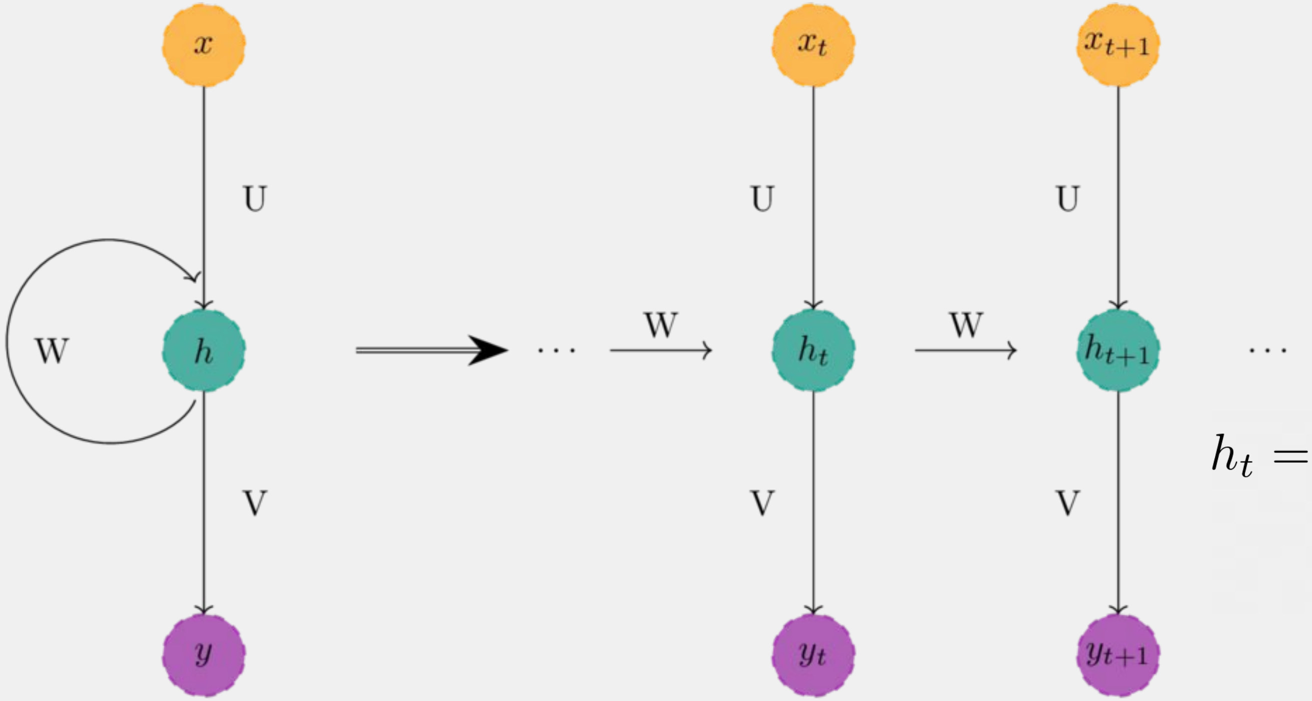


$$z_k = \sigma\left(\sum_{i}^{m} w_i \cdot x_i + b_k\right)$$

$$w_i = w_i - \left(\alpha \times \frac{\partial C}{\partial w_i}\right)$$

$$b_i = b_i - \left(\alpha \times \frac{\partial C}{\partial b_i}\right)$$

Rapid Detour: Recurrent Neural Networks



$$h_t = \sigma_h\Big(Ux_t + Wh_{t-1} + b_h\Big)$$

$$y_t = \sigma_h\Big(Vh_t + b_y\Big)$$

Recurrent Inference Machines

How does a Recurrent Inference Machine work:

Solve the linear equation ***Ax=b*** *iteratively by using an RNN to update solution*

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$$

$$x_{n+1} = x_n - \boxed{}$$

$$x_{n+1} = x_n - \nabla_{\mathrm{RIM}} x_n$$

Putzky & Welling 2017
arxiv.org/abs/1706.04008

Morningstar et al. 2018
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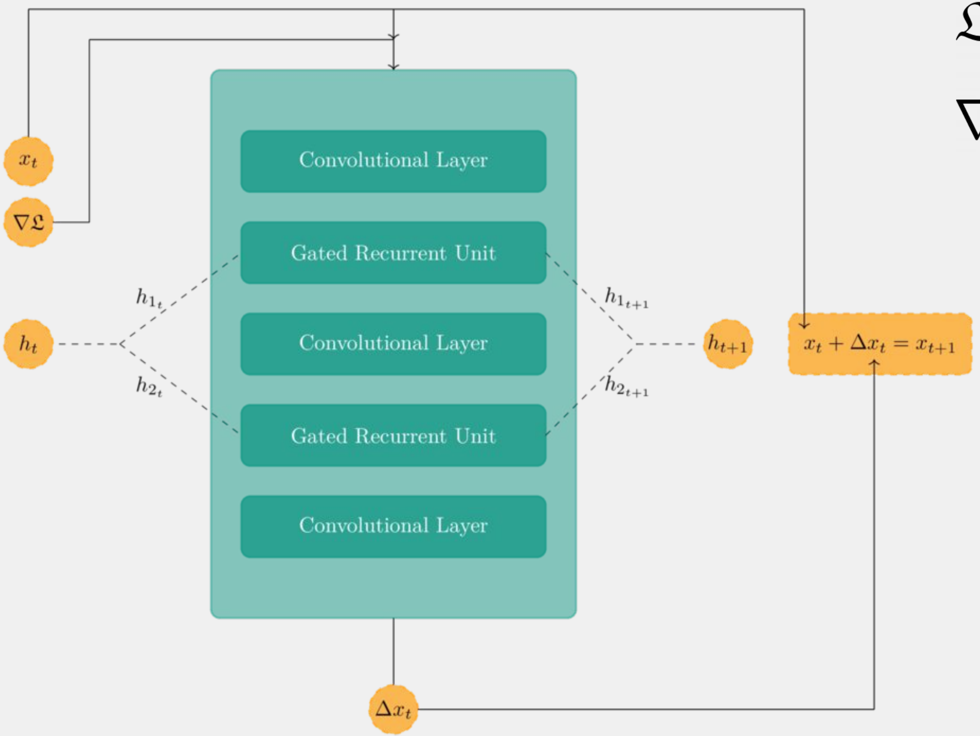


$$\mathfrak{L}_t = -\frac{1}{2}(\mathbf{y} - A\mathbf{x}_t)^T N^{-1}(\mathbf{y} - A\mathbf{x})$$

$$\nabla\mathfrak{L}_t = (\mathbf{y} - A\mathbf{x})^T N^{-1} A$$

Putzky & Welling 2017
arxiv.org/abs/1706.04008

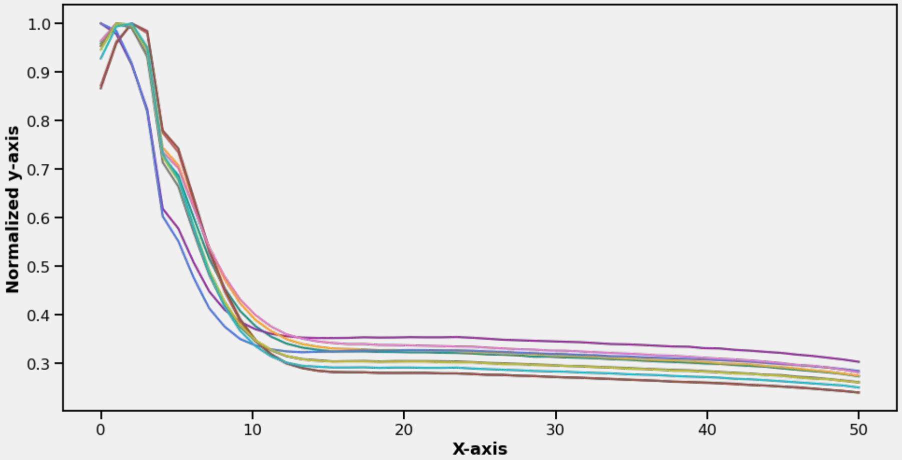
Morningstar et al. 2018
arxiv.org/abs/1808.00011

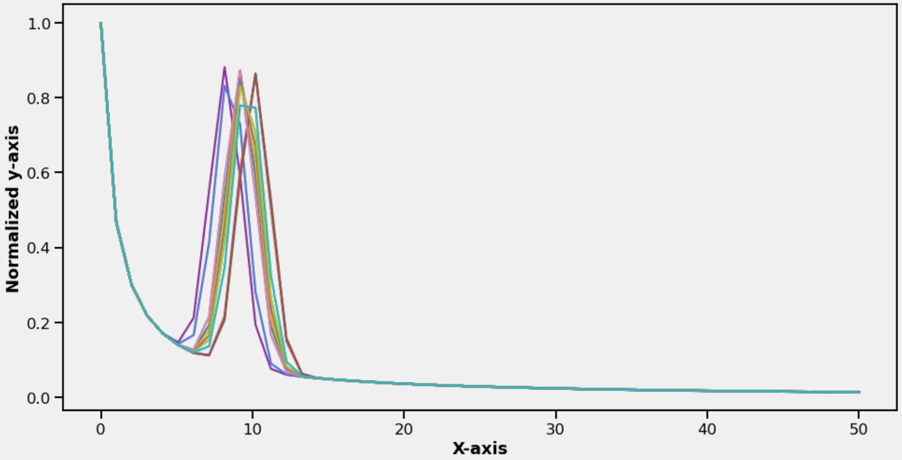
Morningstar et al. 2019
arxiv.org/pdf/1901.01359.pdf

A Simple 1-D Example

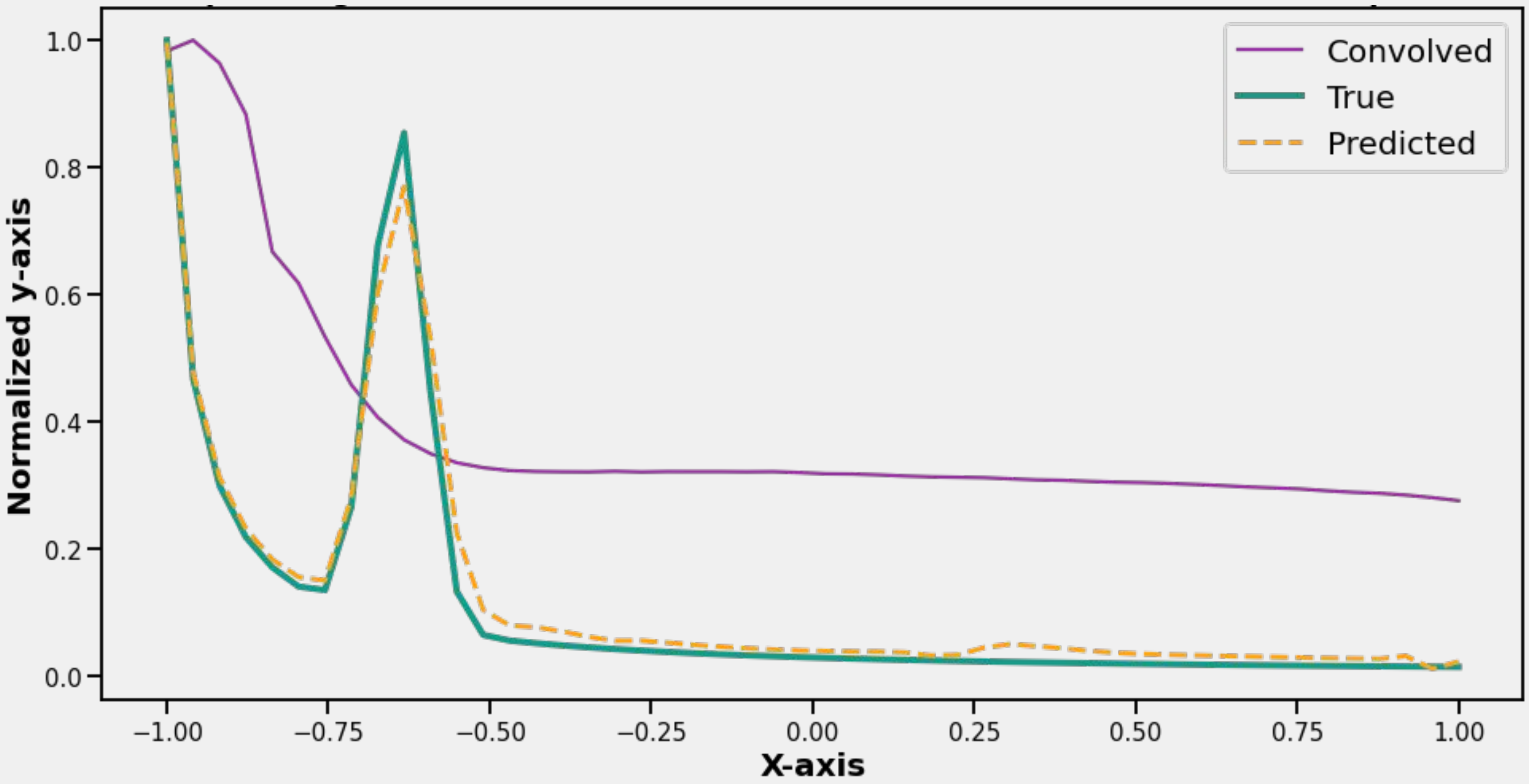
Setup: (Powerlaw + gaussian) convolved with randomly selected Response Matrix plus noise

Test: Can we recover the intrinsic spectrum



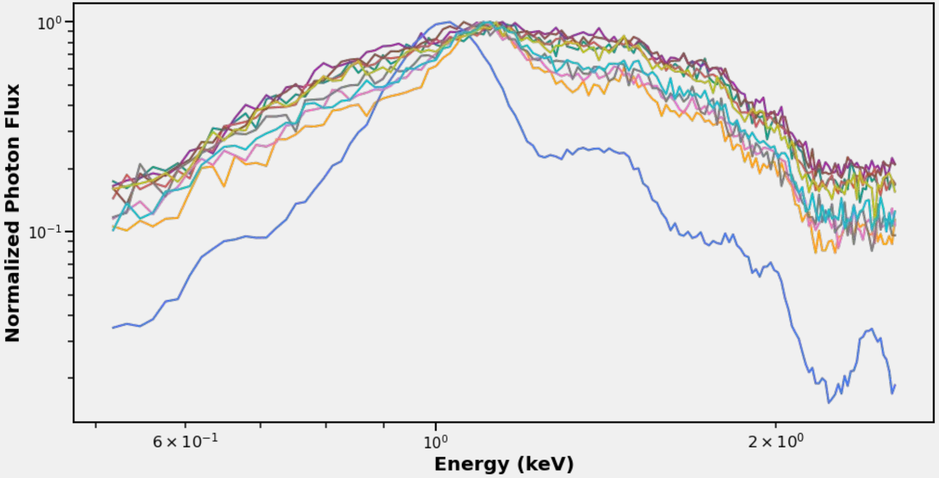


A Simple 1-D Example Continued

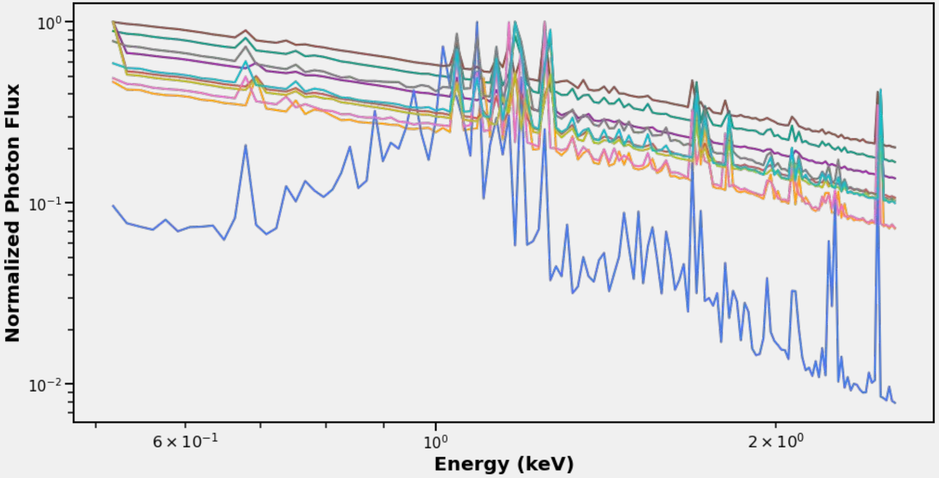


Application to Model X-ray Spectra

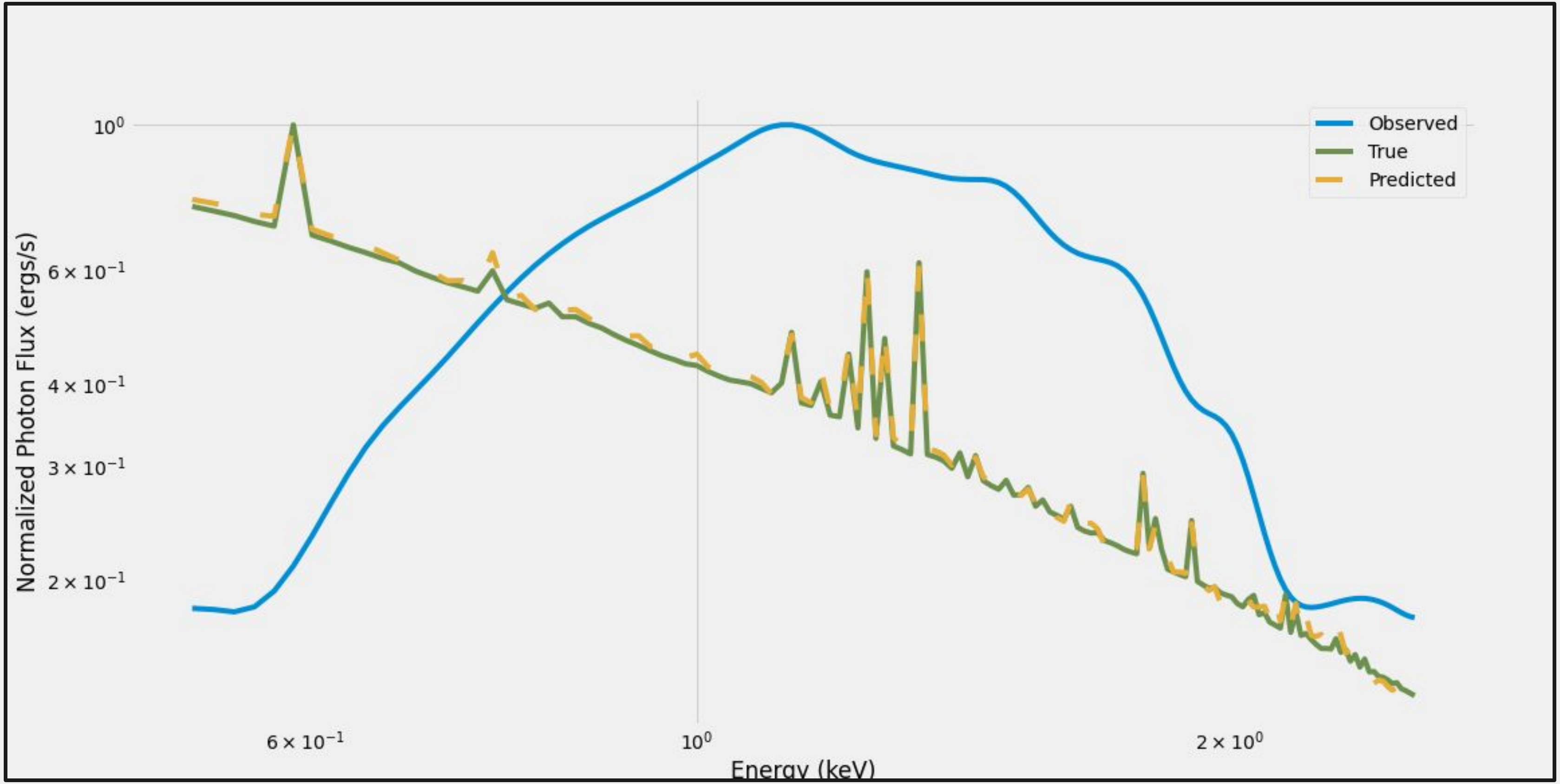
Observed Spectra



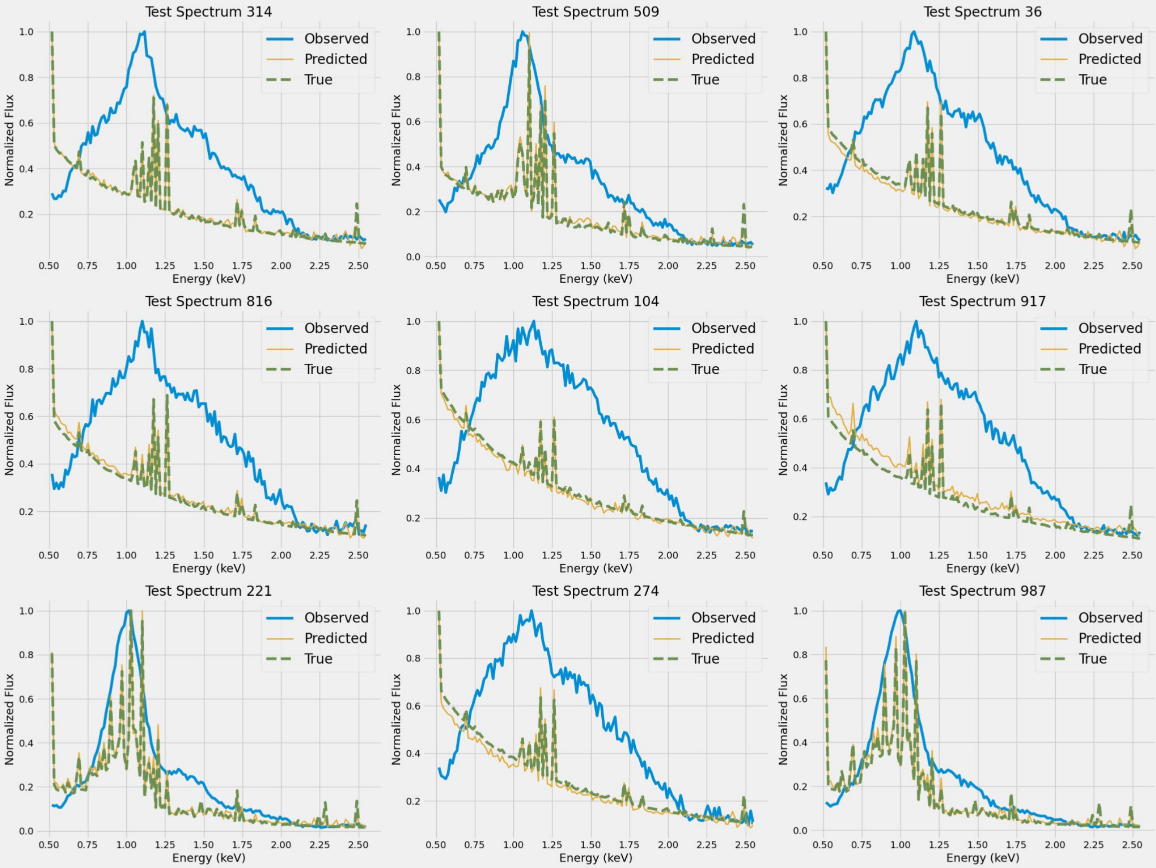
True Spectra



Application to Model X-ray Spectra

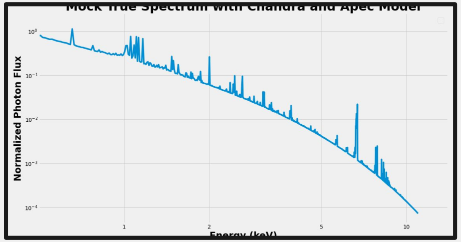


Application to Model X-ray Spectra



Next Steps

What can we do with this?



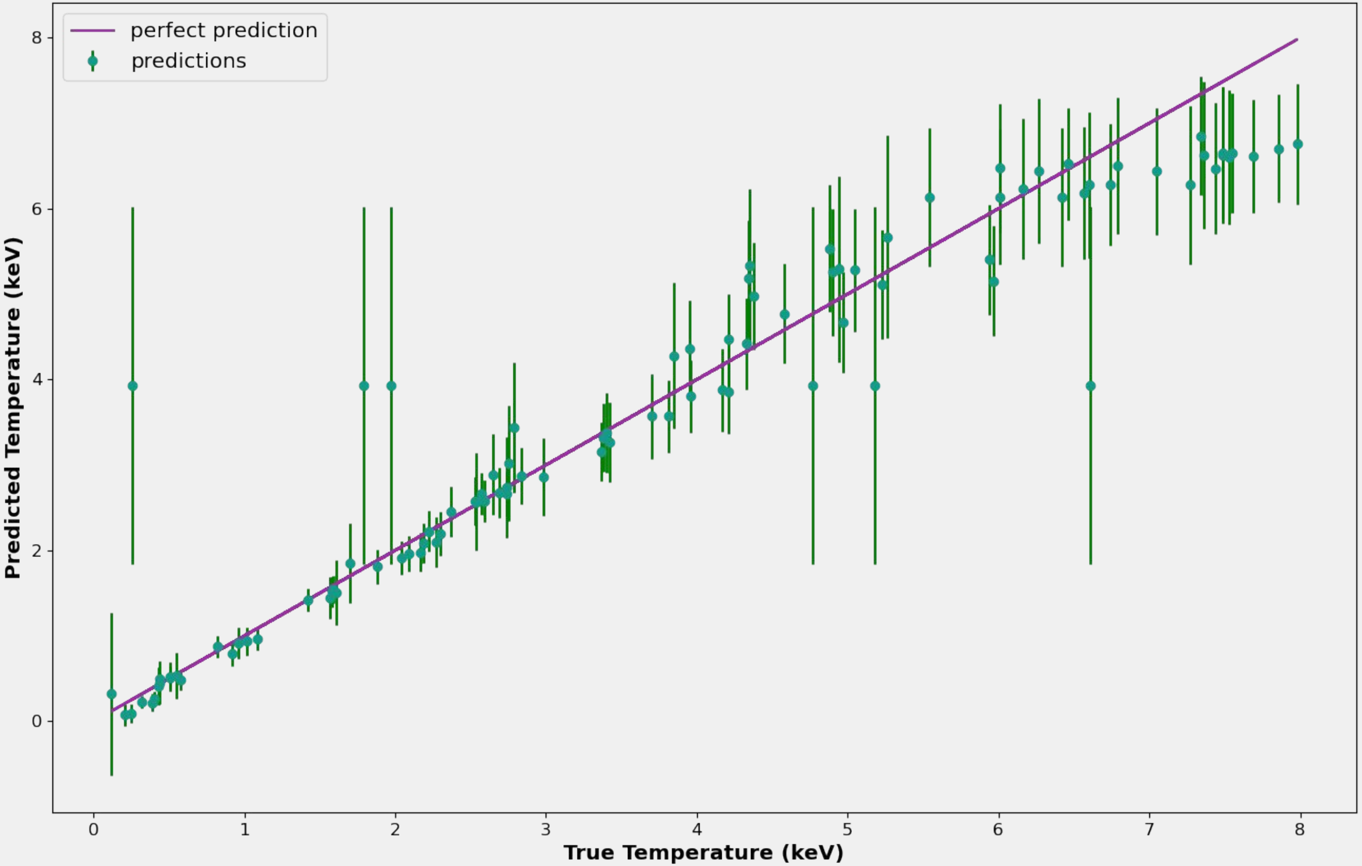
Stack X-ray spectra from all epochs
Rhea et al.

Transient X-ray Sources

By using a calibrator, derive Chandra calibration
Prunier, Rhea, JHL et al.

Parameter Estimation with Neural Networks
Rhea et al.

Estimate Temperature



RESULTS NOT USING RIM ARE SHOWN

ANY IDEAS WELCOME!

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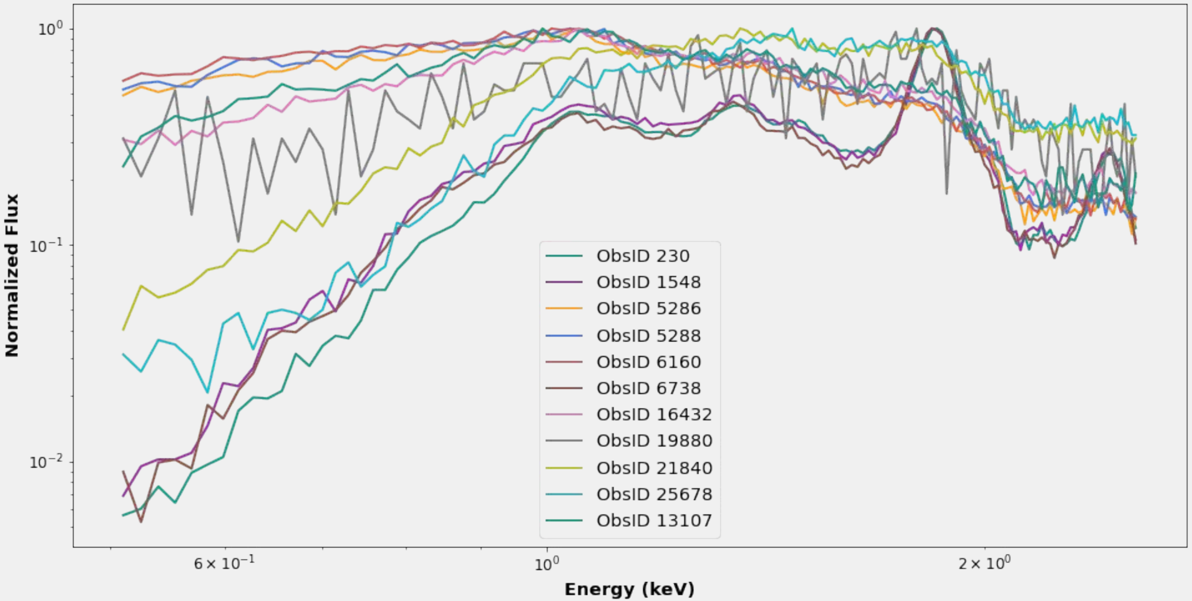
Chandra Calibration

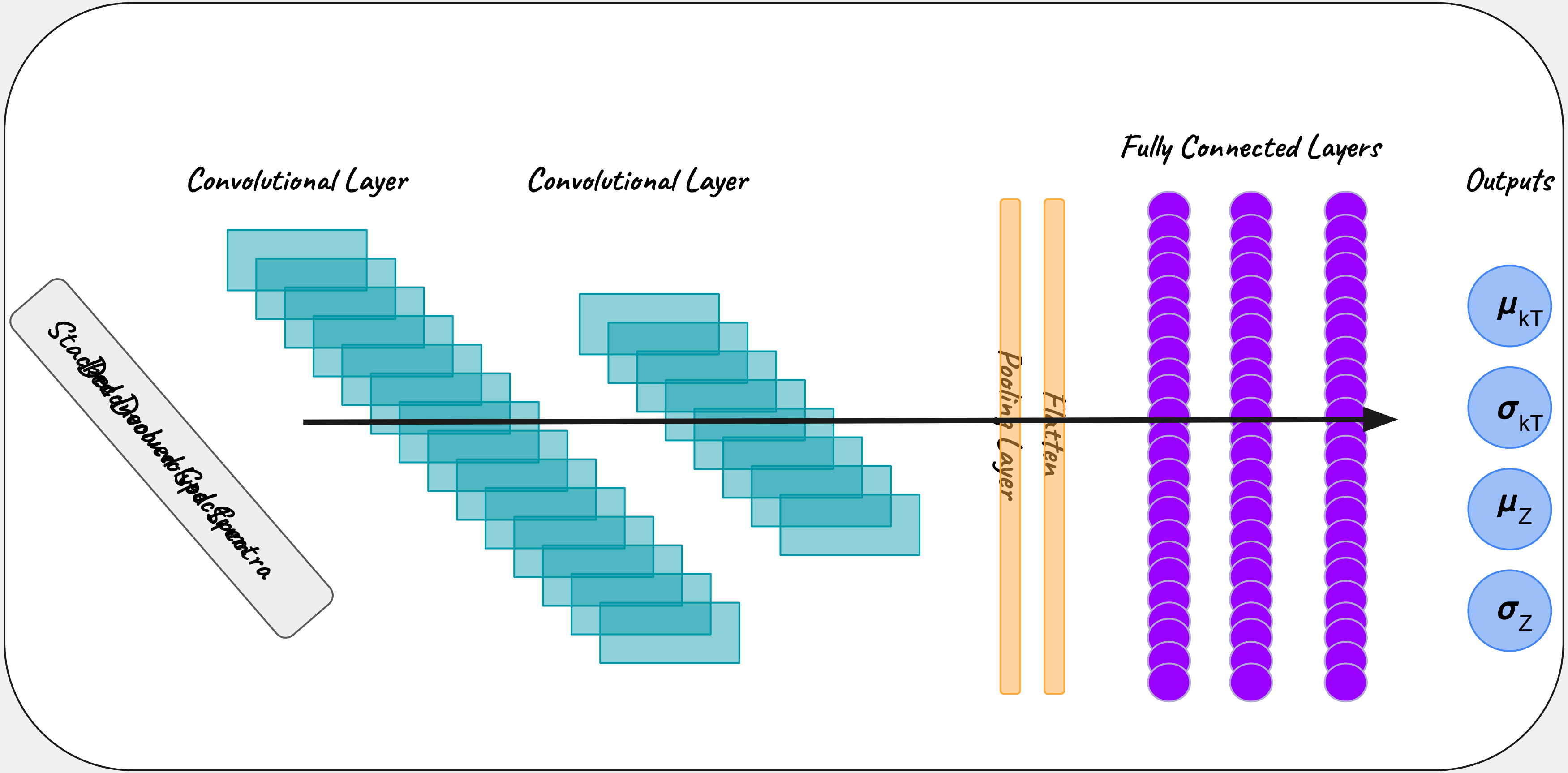
Goal: Evaluate ACIS calibration using the RIM

Method:

1. Select stable source (Abell 1795)
2. Compare deconvolved sources
   They should be identical
3. Learn correct form of Response Matrices



Estimate Temperature and Metallicity



Putting it all together!

Preprocessing (RIM)

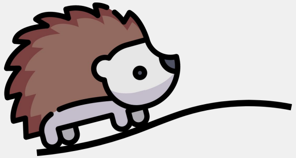
Deconvolve X-ray Spectra s/t we can stack them

Mixture Density Network

Train MDN on deconvolved spectra to obtain posterior distributions of temperature and metallicity

Bayesian Inference (BXA)

Use MDN results as priors to do a full Bayesian inference approach to X-ray Spectral Fitting



Rhea, C. et al, AJ 160, 5 (2020)

Buchner, J. et al, A&A 564, A125 (2014)