Calibration of the Soft X-ray Telescope (SXT) Response Files of AstroSat
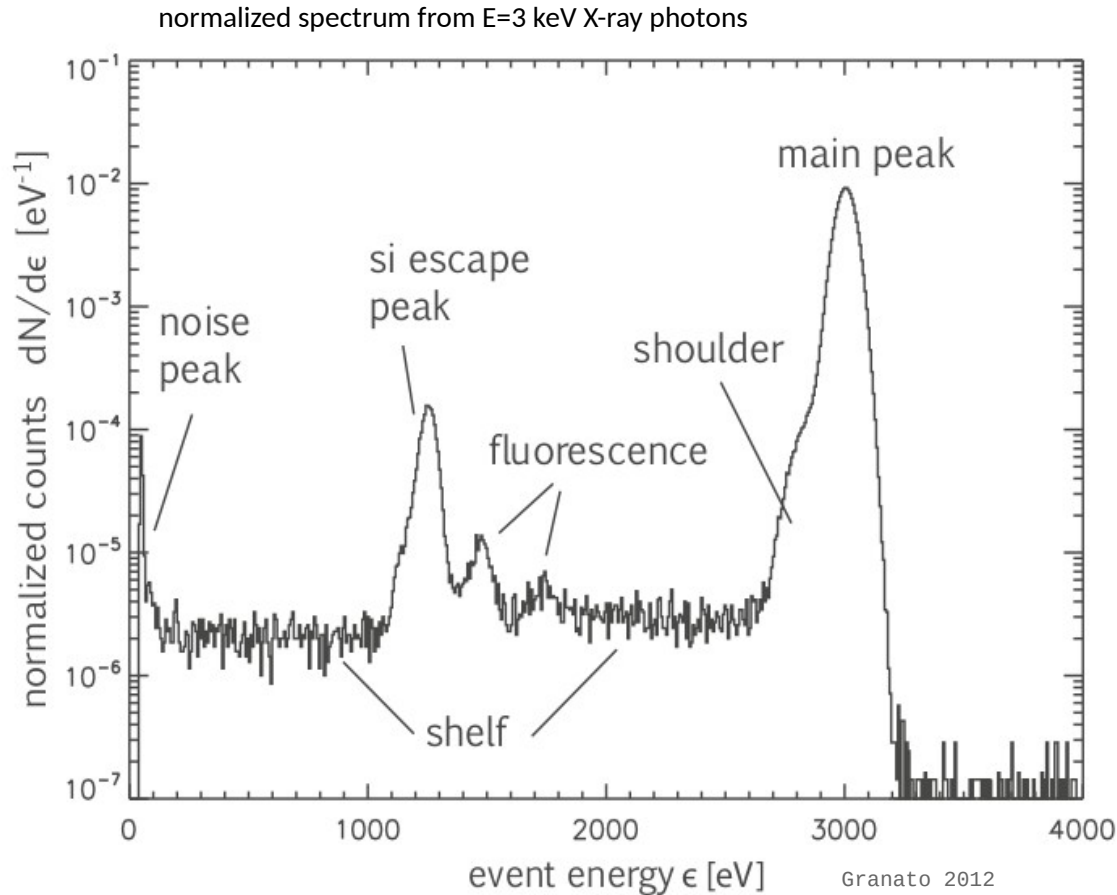
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IUCAA

Dec 9, 2025

Spectral Redistribution

normalized spectrum from E=3 keV X-ray photons

Granato 2012

- **Main peak:** The primary peak of the incident photons (~ Gaussian with a more or less distinct shoulder at the low-energy side of the main peak)

- **Fluorescence Peaks:** when incident high-energy photons excite (e.g., silicon atoms) in the detector material, causing characteristic X-ray emission as electrons transition to lower energy states.

- **Escape peak:** Events with an energy reduced by the fluorescence photon energy.

- **Noise peak:** noise fluctuations during readout that are above the event detection threshold.

A typical X-ray spectrum shows the **main peak and additional off-peak features**, as fluorescence peaks and the flat shelf. The main peak exhibits a low energy shoulder caused by charge loss in the entrance window.
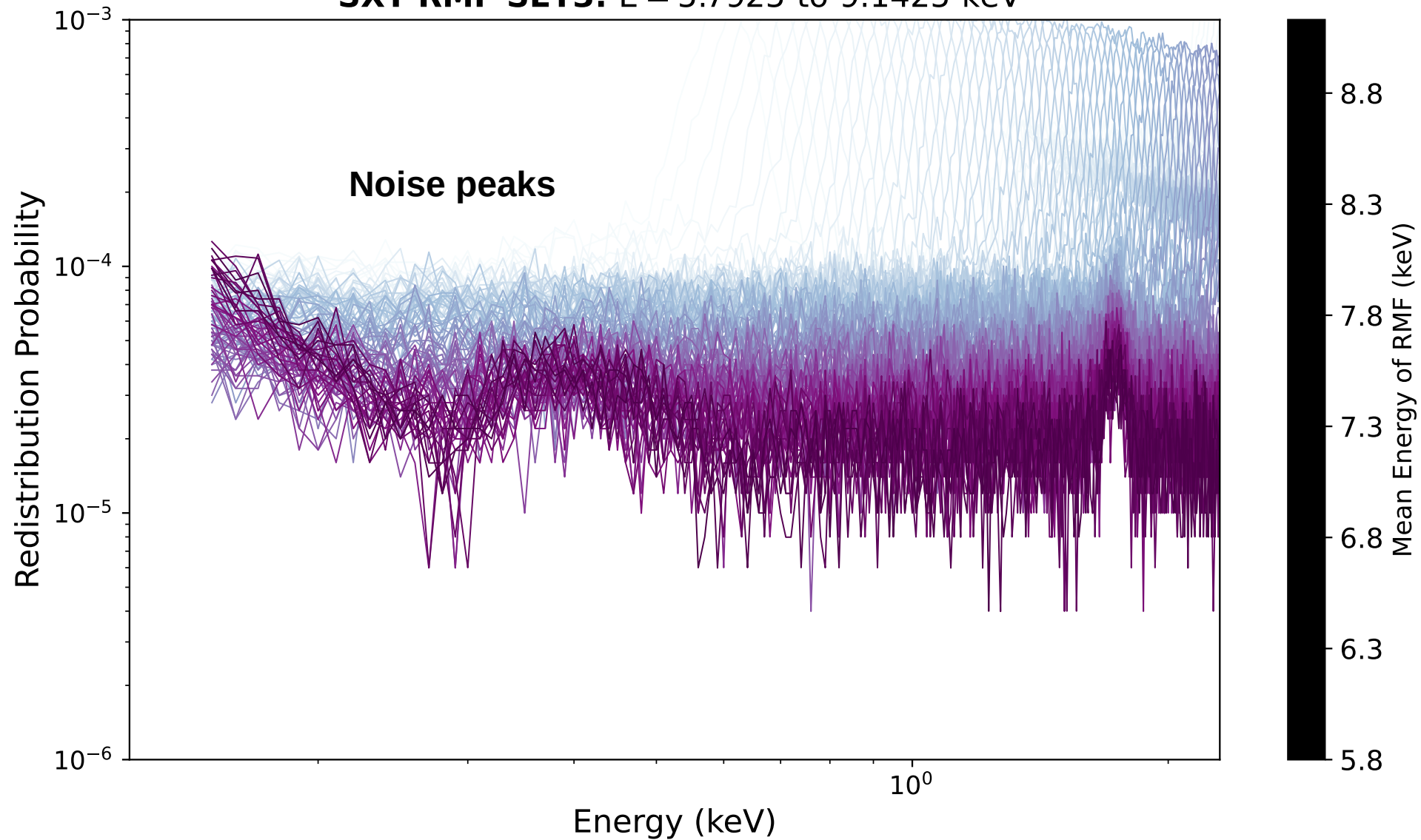
RMF of SXT/AstroSat

SXT RMF SET1: Ē = 0.4175 to 1.8375 keV; Mainpeak + Shoulder

Main Peak

shoulder

Redistribution Probability

Energy (keV)

Mean Energy of RMF (keV)
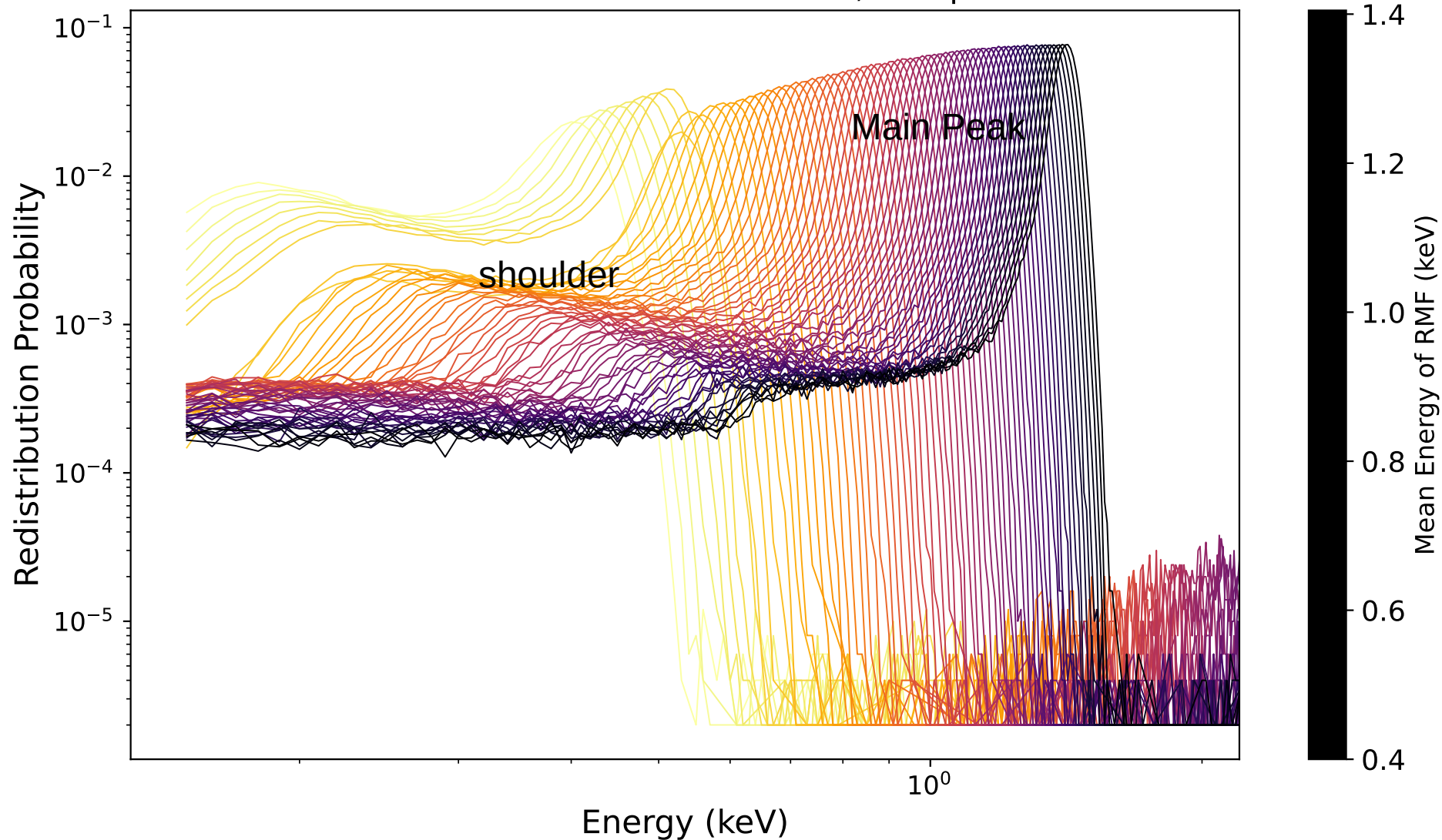
SXT RMF SET2: $\bar{E}$ = 1.8425 to 5.7875 keV
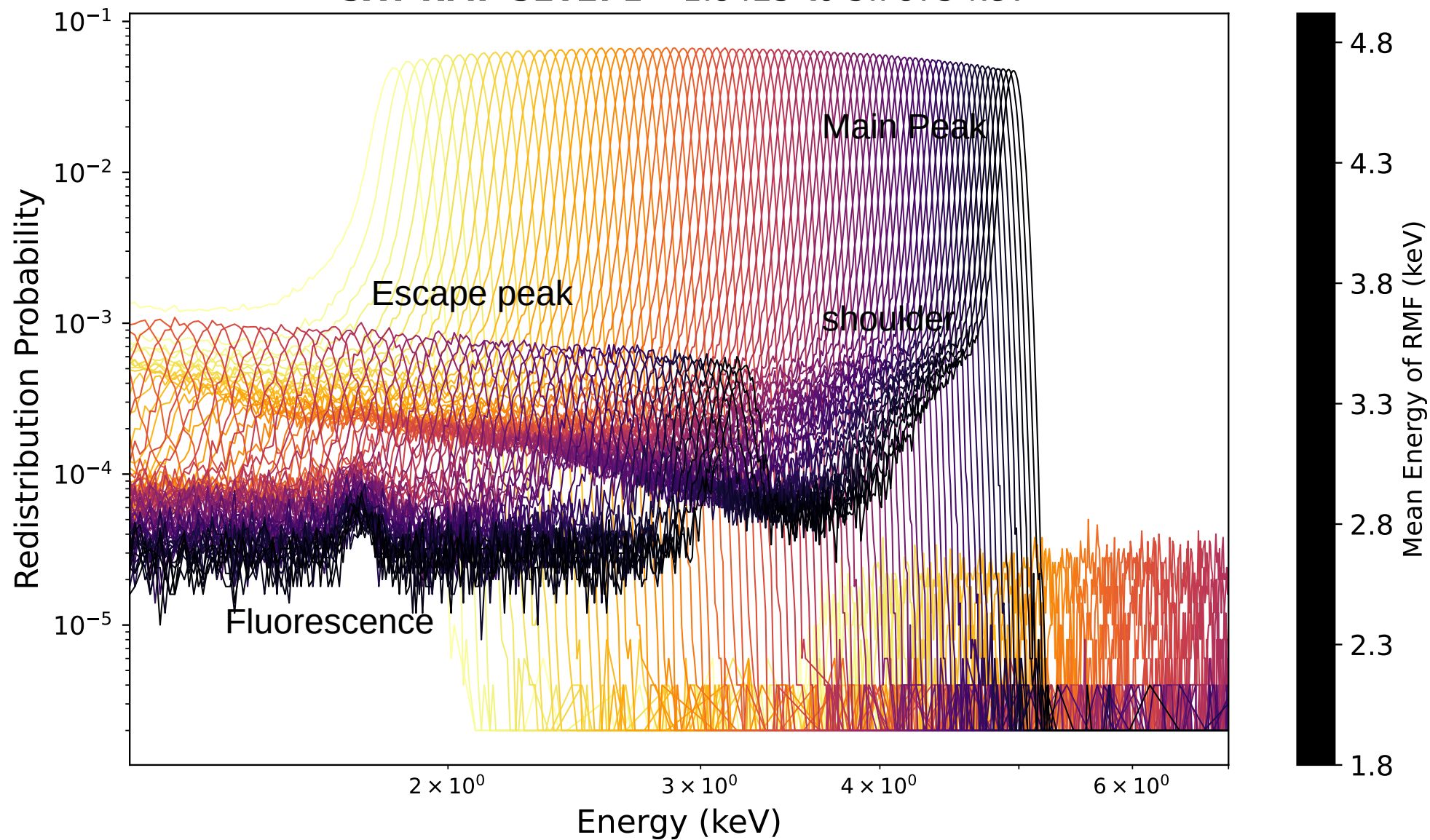
SXT RMF SET3: $\bar{E} = 5.7925$ to 9.1425 keV

Noise peaks

Redistribution Probability

Energy (keV)

Mean Energy of RMF (keV)

Parameterization of RMF of SXT/AstroSat

The spectral re-distribution for a input X-ray photon energy E_{in} can be expressed by the integral :

$$N(E) \propto \int_0^D e^{-\mu(E_{in})x} e^{-\frac{(E - E_{in}f(x))^2}{2\sigma^2}} dx$$

We use the simple analytical functions used in Godet, O. et. al. 2008 in modelling the spectral response of the Swift-XRT CCD:
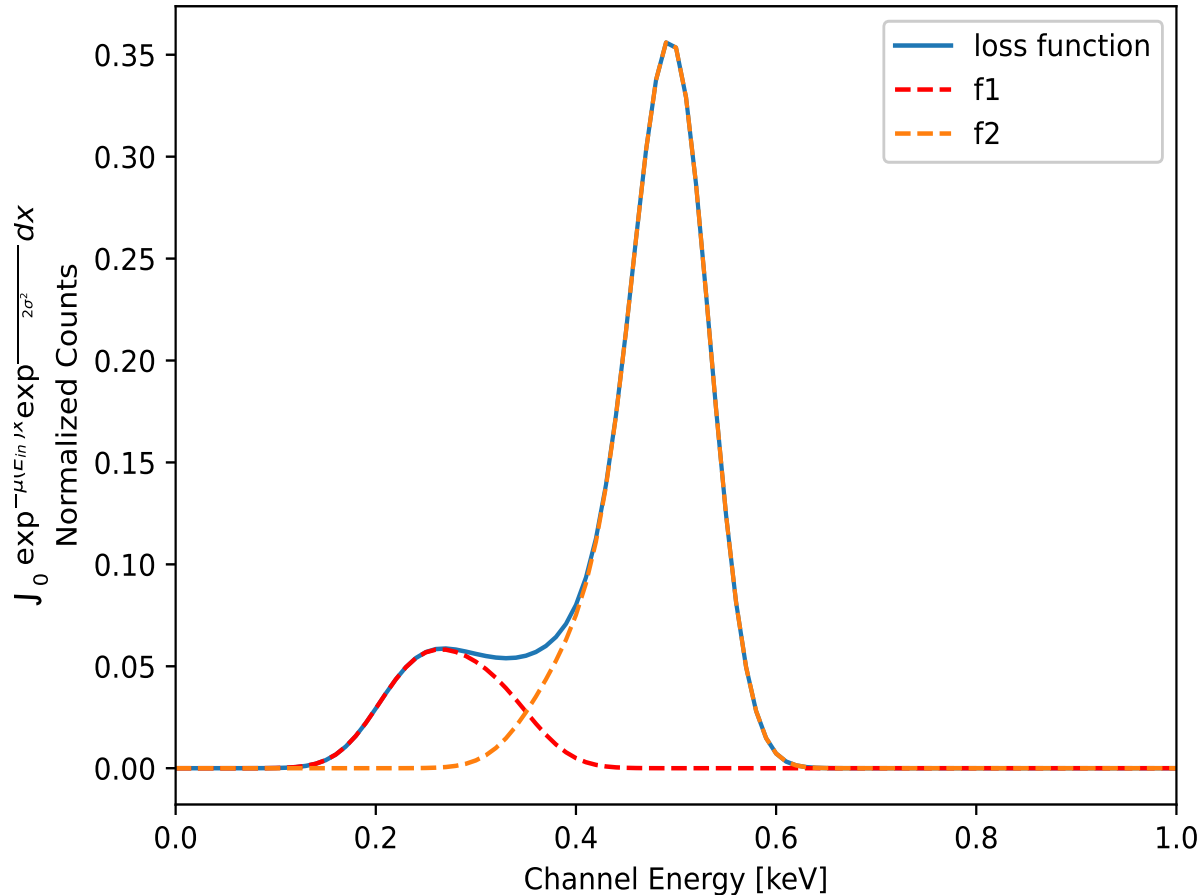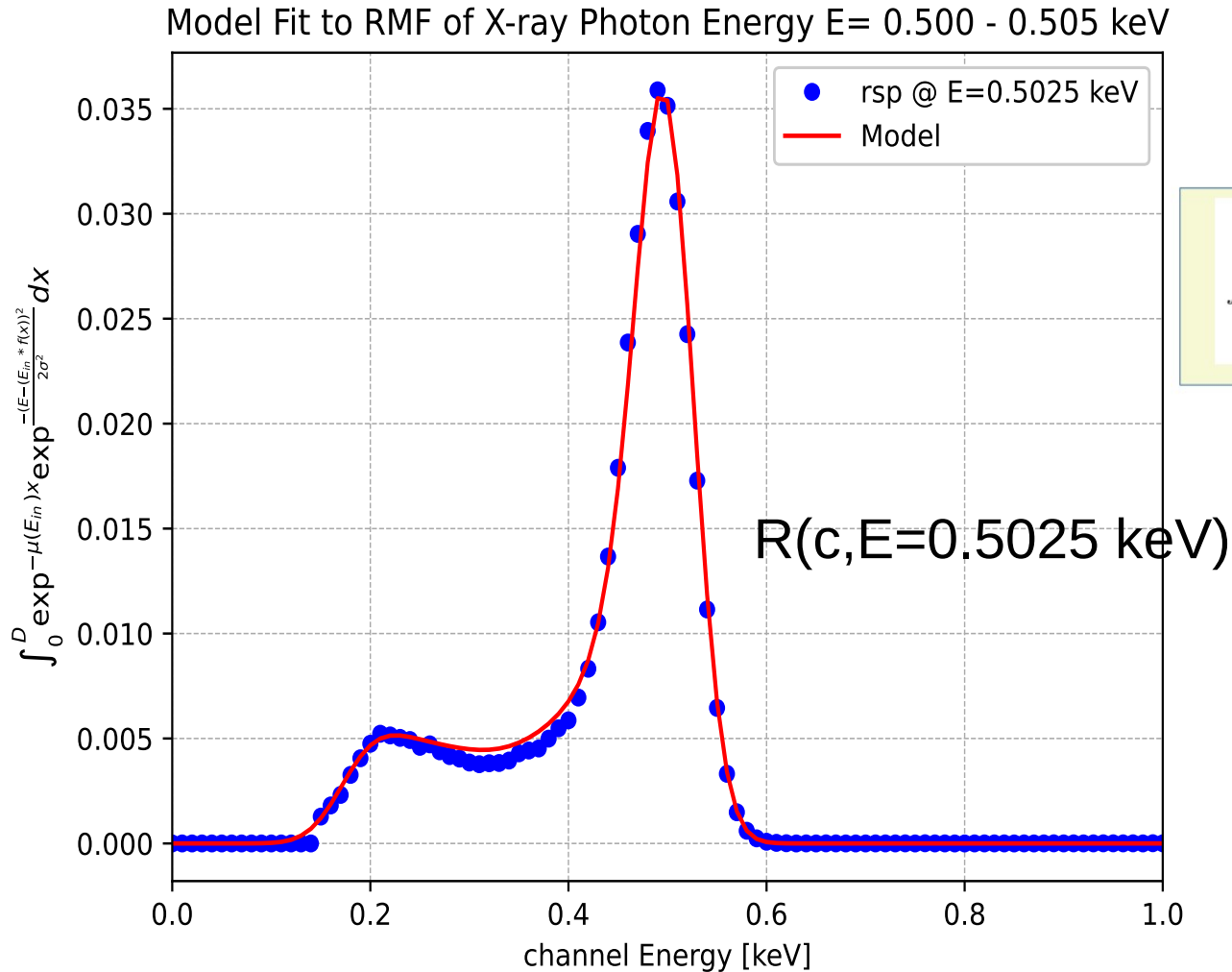
$$f(x) = \begin{cases} 0, & x < 0 \\ f0 + \alpha \left(\frac{x}{l}\right)^\beta, & 0 \leq x \leq l \\ 1 - \gamma e^{-\frac{x-l}{\tau}}, & l \leq x \leq D \end{cases}$$

$\longrightarrow$ Loss function1

$\longrightarrow$ Loss function2

Example: Original and recomputed RMF at 0.5025 keV

Model Fit to RMF of X-ray Photon Energy E= 0.500 - 0.505 keV

$$f(x) = \begin{cases} 0, & x < 0 \\ f0 + \alpha \left(\frac{x}{l}\right)^{\beta}, & 0 \leq x \leq l \\ 1 - \gamma e^{-\frac{x-l}{\tau}}, & l \leq x \leq D \end{cases}$$

→ Loss function1

→ Loss function2

**Main peak model parameters:**

l, tau, f0, beta, sigma, norm

Example: Original and recomputed RMF at 0.5025 keV

Model Fit to RMF of X-ray Photon Energy E= 0.500 - 0.505 keV

$$\int_0^D \exp^{-\mu(E_{in})} \times \exp^{-\frac{(E-(E_{in}*f(x))^2}{2\sigma^2}} dx$$

channel Energy [keV]

- rsp @ E=0.5025 keV
— Model

R(c,E=0.5025 keV)

$$f(x) = \begin{cases} 0, & x < 0 \\ f0 + \alpha \left(\frac{x}{l}\right)^\beta, & 0 \leq x \leq l \\ 1 - \gamma e^{-\frac{x-l}{\tau}}, & l \leq x \leq D \end{cases}$$

⟹ Loss function1
⟹ Loss function2

Main peak model parameters:

l, tau, f0, beta, sigma, norm

Choosing Best Model for RMF

R(E,Ein=1.0025 keV)
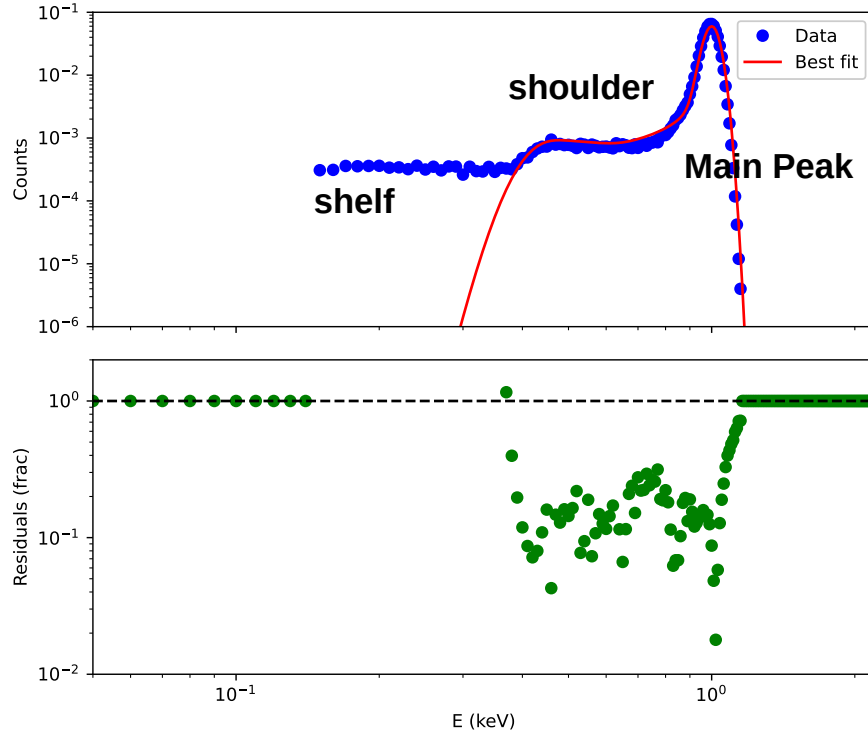
Main Peak + Shoulder (Rs):

$$R_s(E, E_{in}) = \int_0^D e^{-\mu(E_{in})x} G(E, f(x, E_{in}) \times E_{in})\, dx$$
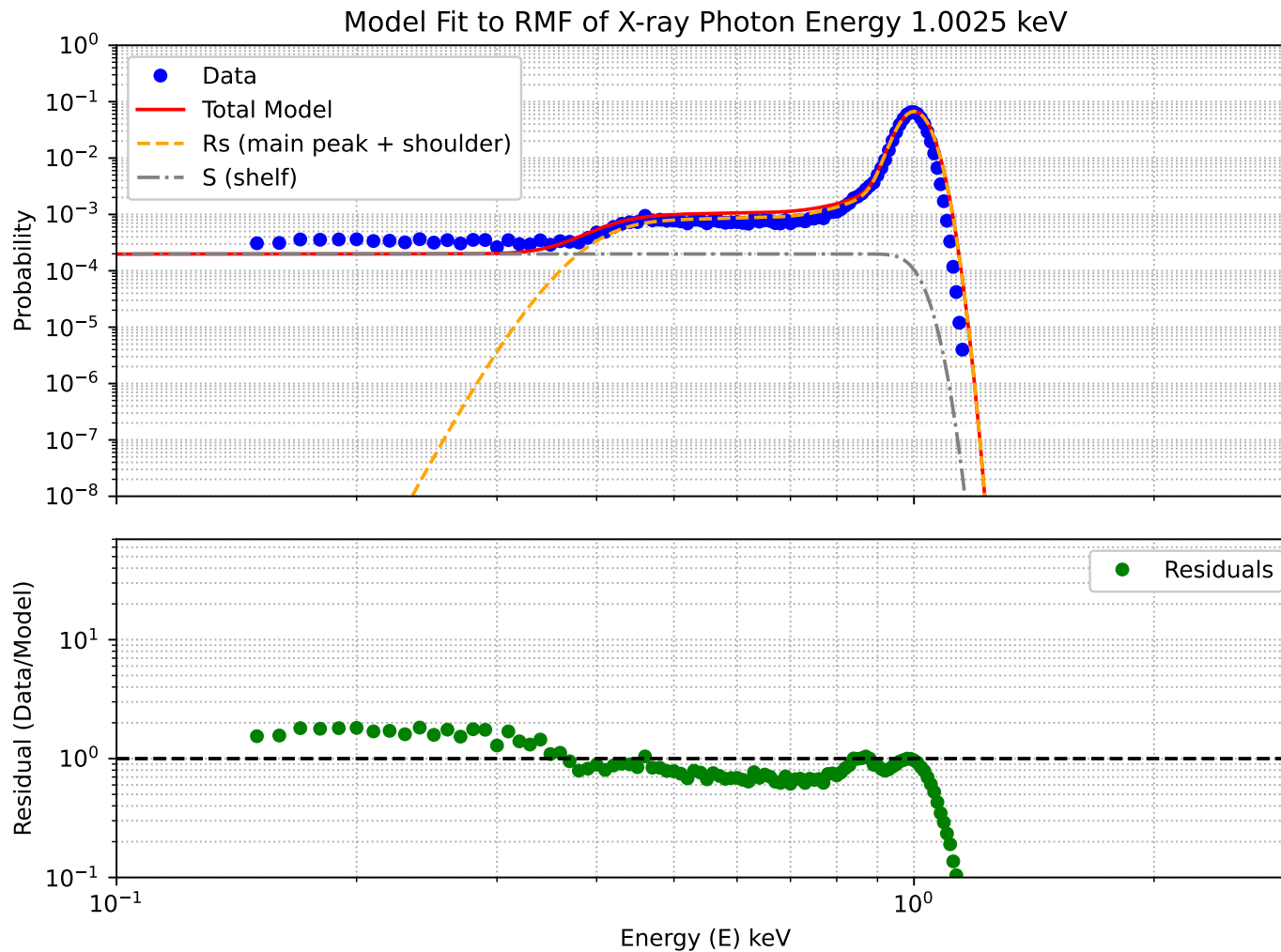
Shelf (S):

$$S(E, E_{in}) = \frac{N_{sh}}{2\pi\sigma(E_{in})} \int_{e_0}^{e_1} \exp\left(-\frac{1}{2}\left(\frac{e}{\sigma(E_{in})}\right)^2\right) de$$

- **Shelf Function (S):** The charge-loss *shelf* in the redistribution matrix is modeled by the equation (ref. *MOS CCD RMF Description*, Document No. EPIC-LUX-RE-170, Version 1.1, 10 February 2000) :
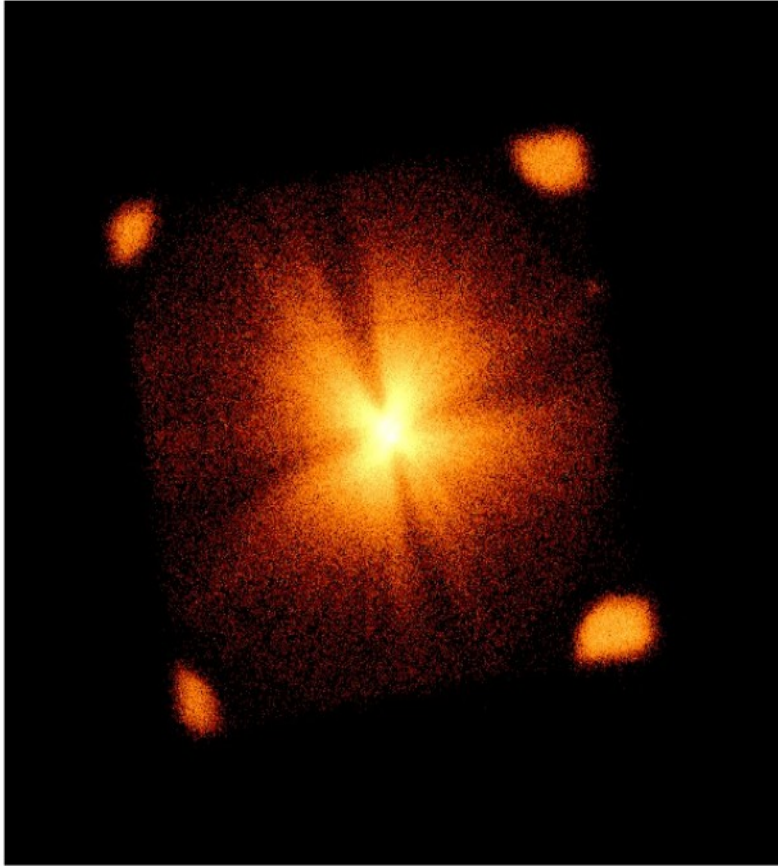
$$S(E, E_{in}) = \frac{N_{sh}}{2\pi\sigma(E_{in})} \int_{e_0}^{e_1} \exp\left(-\frac{1}{2}\left(\frac{e}{\sigma(E_{in})}\right)^2\right) de \qquad (5)$$
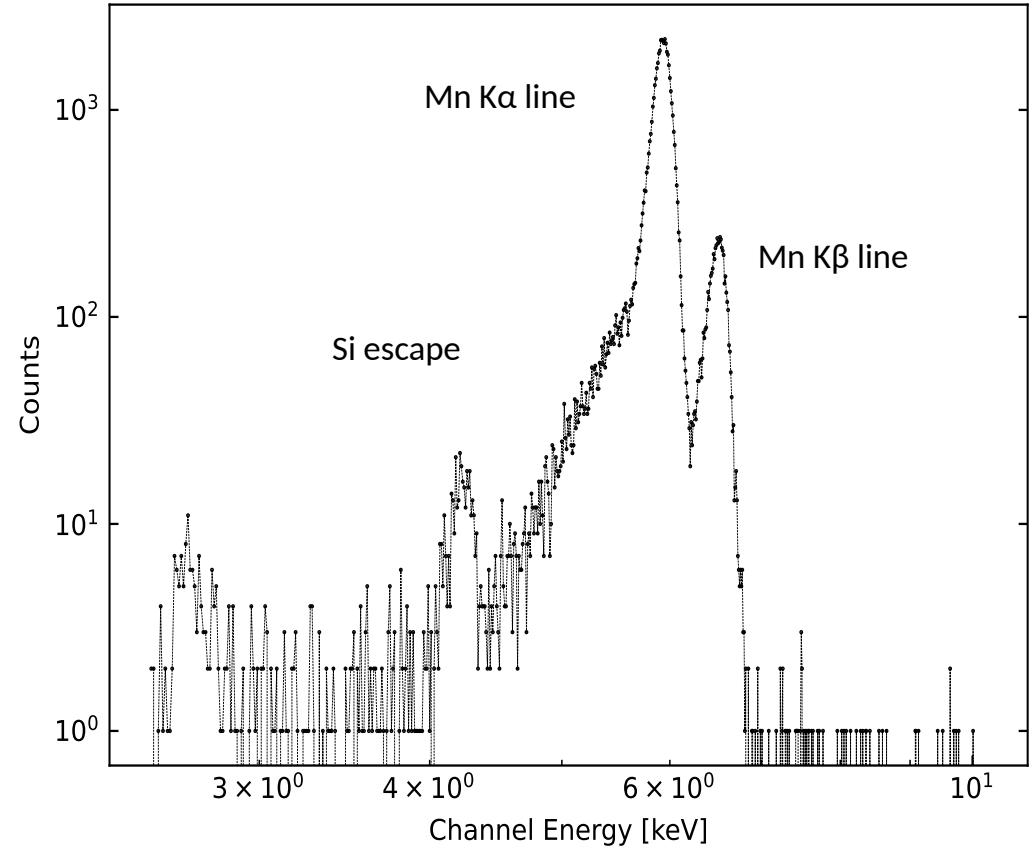
where $e_0 = -E$ and $e_1 = E_{in} - E$.

Example Model Fit for RMF

Model Fit to RMF of X-ray Photon Energy 1.0025 keV

Iron-55 radioactive calibration sources
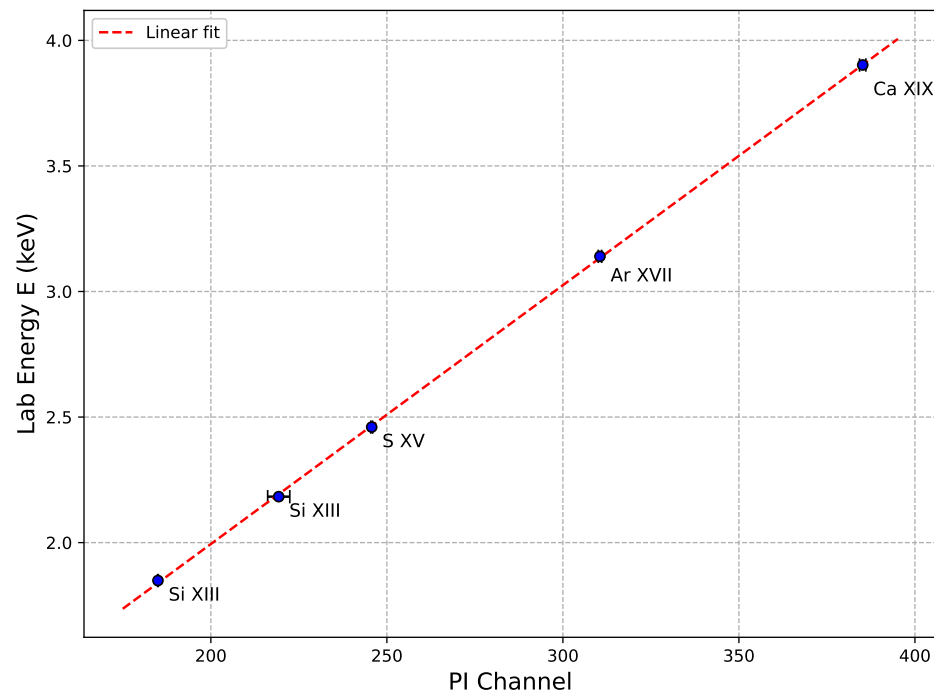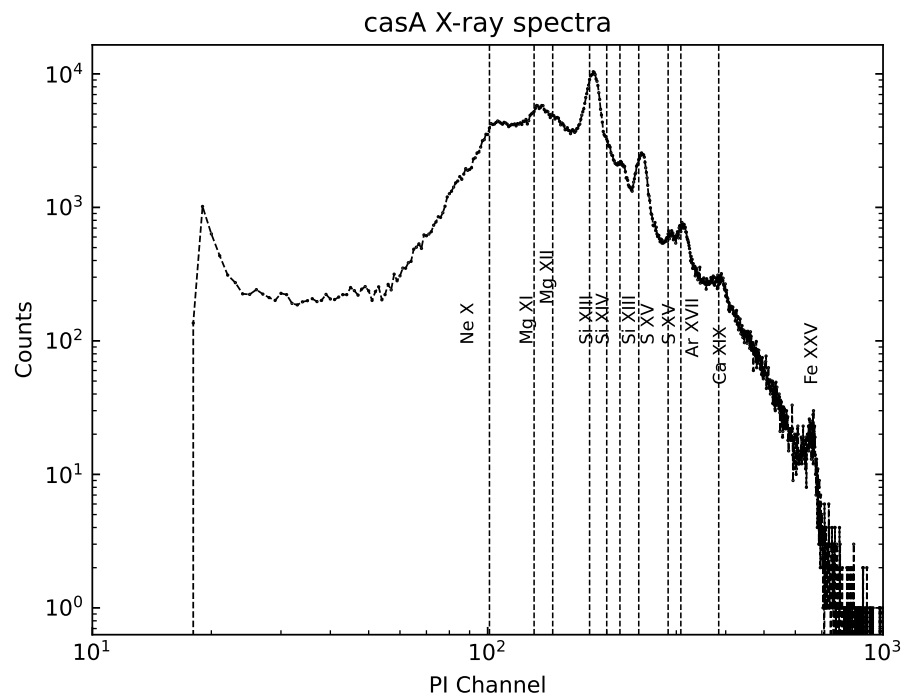

CCD illuminated by the Four 55Fe radioactive calibration sources (in the 4 corners) that are provided in the camera for in-flight calibration of astrosat.
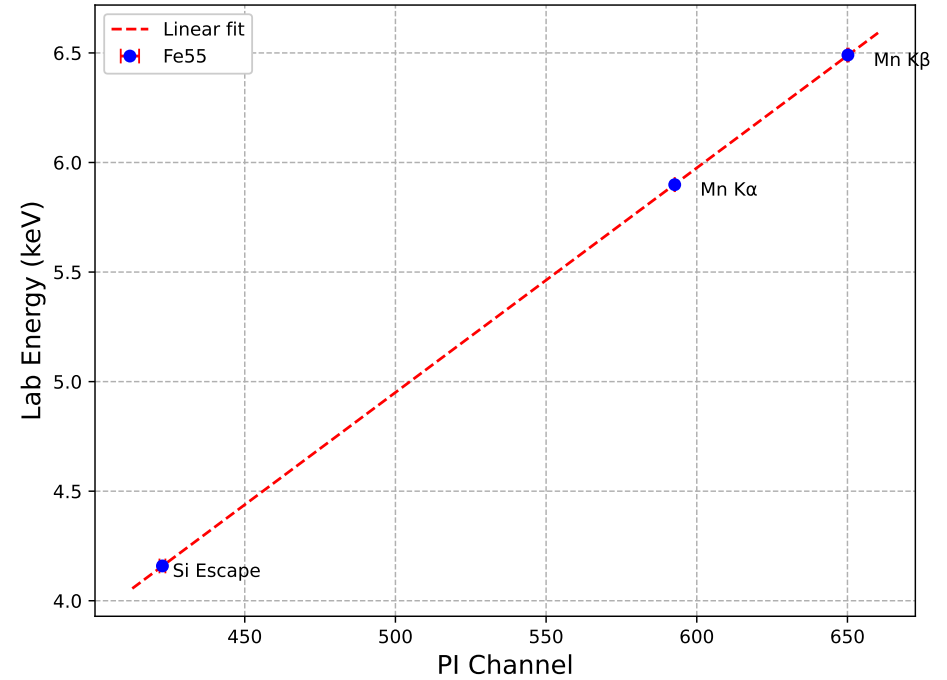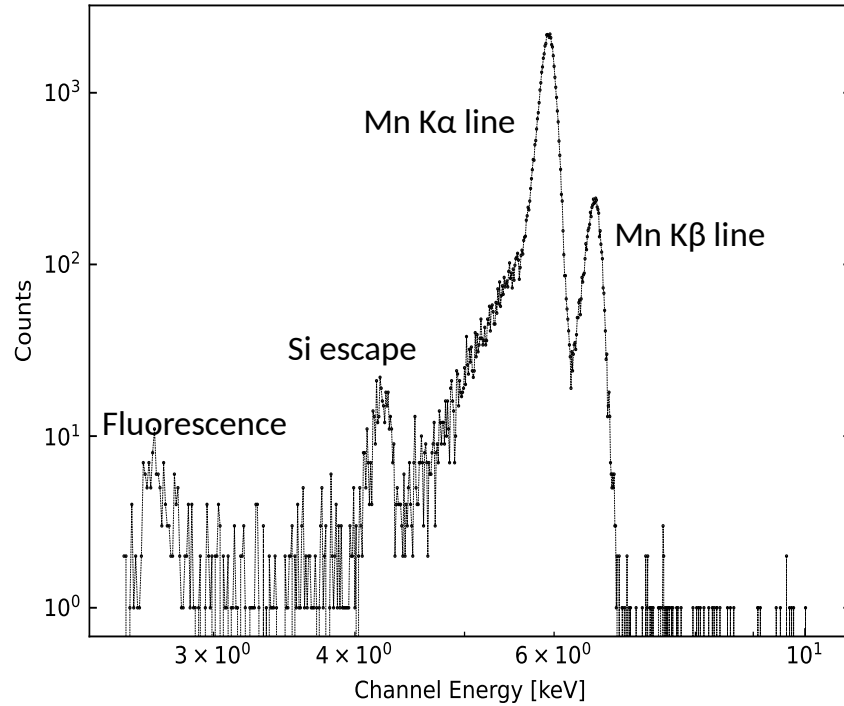

X-ray line flux of the Mn Kα line at 5.9 keV from the decay of 55Fe, Mn Kβ (6.5 keV), Si escape (4.2 keV)
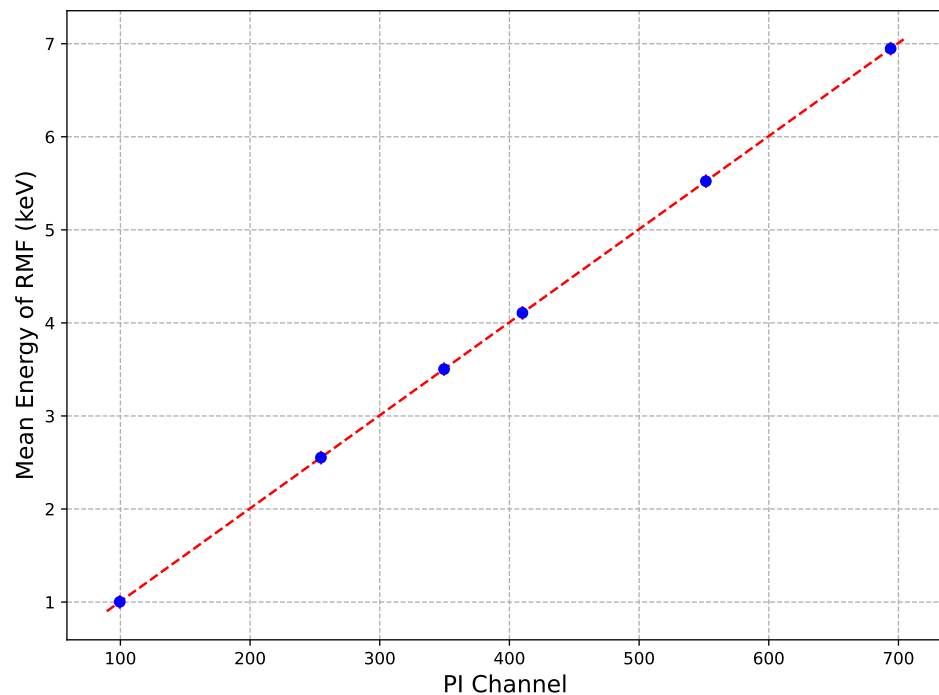Offset = +0.04 keV

Energy Calibration Using: cassiopeia A

$$E \text{ (keV)} = 0.010306 \times PI - 0.066922$$
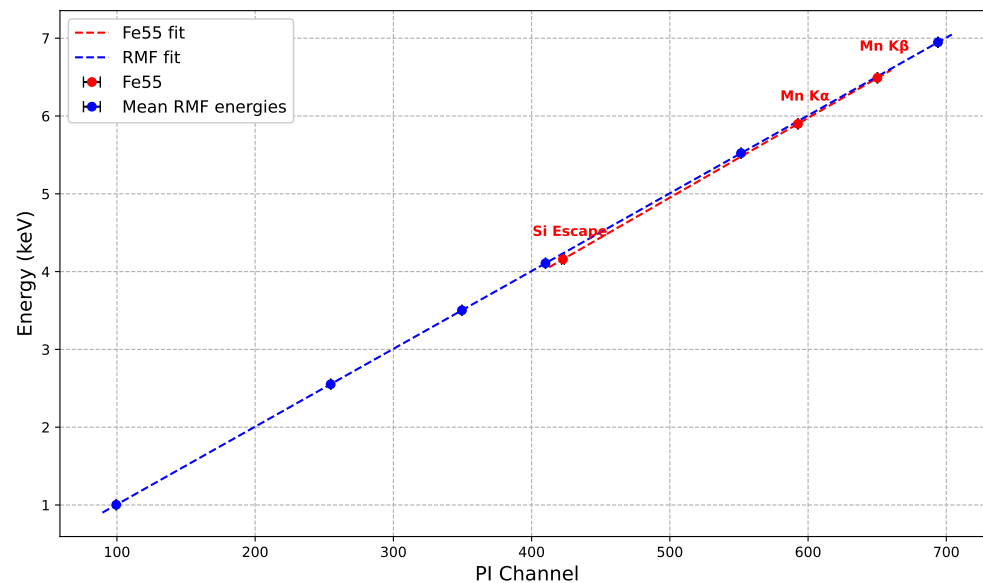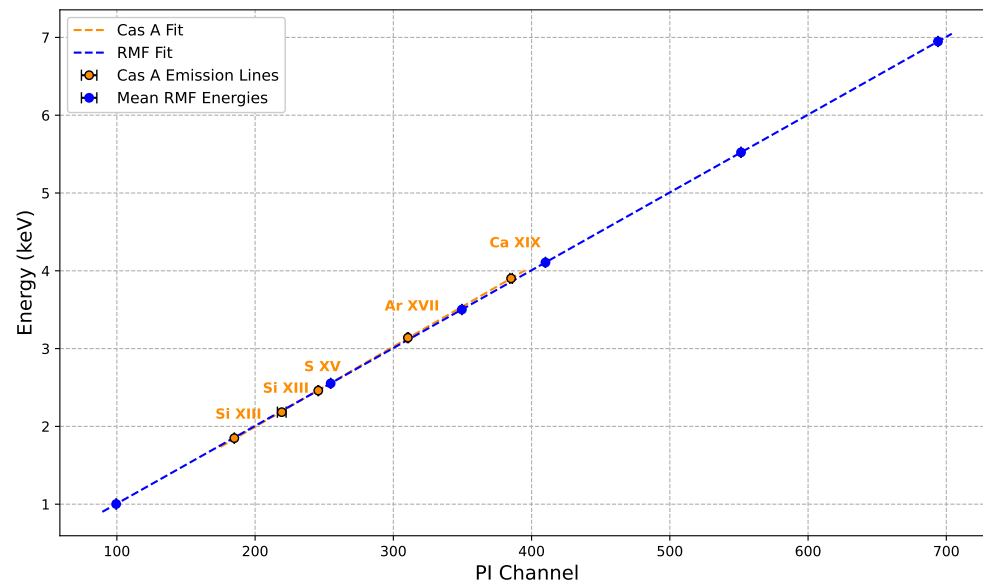
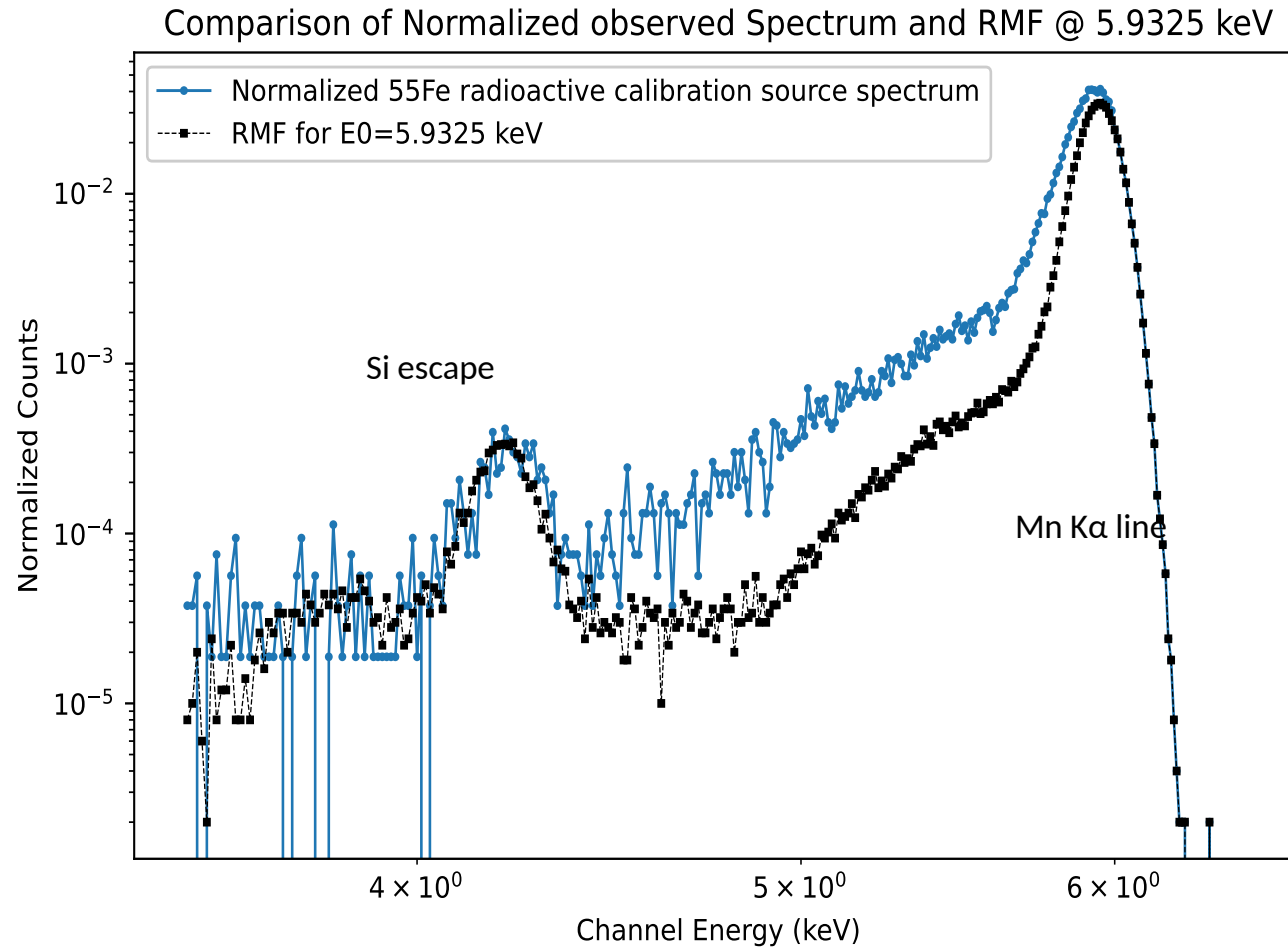# Energy Calibration Using: Fe55

E (keV) = 0.010247 × PI - 0.172793

RMF Mean Energy vs Fitted Centroid PI Channel

$$E \ (keV) = 0.010001 \times PI + 0.006525$$

The Iron-55 radioactive calibration source spectrum

Comparison of Normalized observed Spectrum and RMF @ 5.9325 keV

- Normalized 55Fe radioactive calibration source spectrum
- RMF for E0=5.9325 keV

Si escape

Mn Kα line

Normalized Counts

Channel Energy (keV)

Modeling the Iron-55 radioactive calibration source spectrum

Model fit to Normalized observed Spectrum
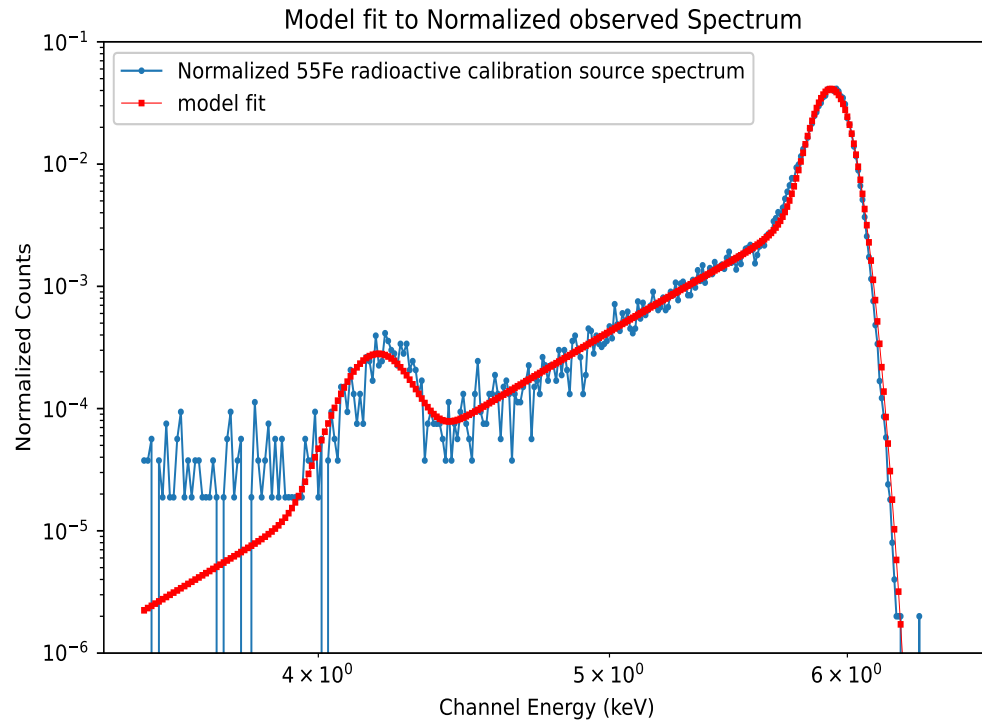
GOAL to update RMF

Find Best fit model parameters- for RMF & Fe55 compare the shift

Demonstration plot Parameter: σ

Fe55 model fit
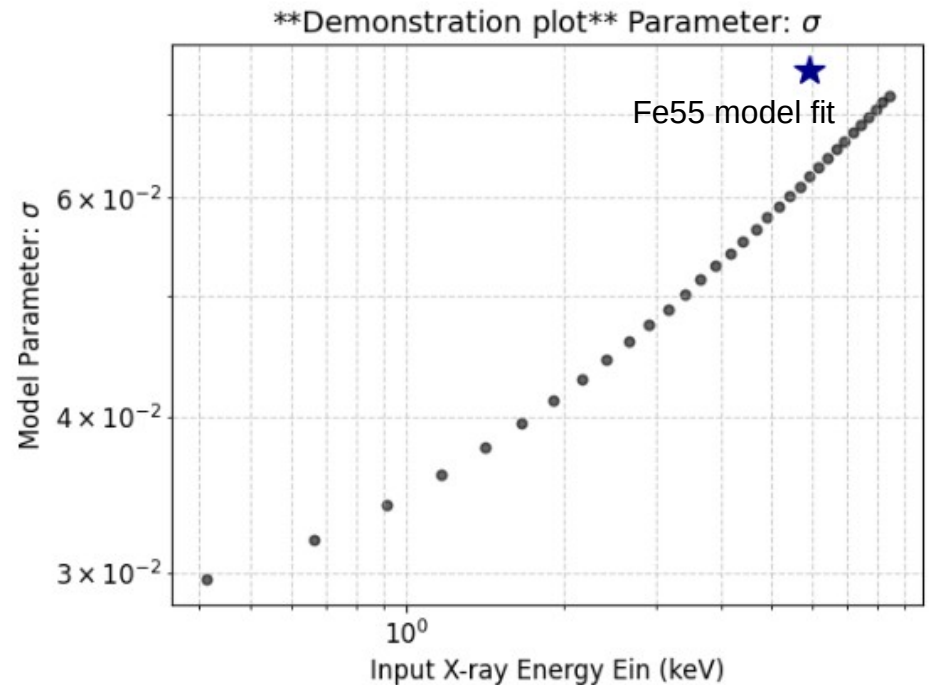
Constraining the model parameters – not so trivial ??

Strong interdependence among model parameters **prevents convergence to a unique global minimum**; the parameters are highly correlated and the fit admits multiple solutions?, undermining the model's ability to uniquely represent the existing RMFs.

$$R_s(E, E_{in}) = \int_0^D e^{-\mu(E_{in})x} G(E, f(x, E_{in}) \times E_{in}) \, dx$$

$$f(x) = \begin{cases} 0, & x < 0 \\ f0 + \alpha \left(\frac{x}{l}\right)^{\beta}, & 0 \leq x \leq l \\ 1 - \gamma e^{-\frac{x-l}{\tau}}, & l \leq x \leq D \end{cases}$$
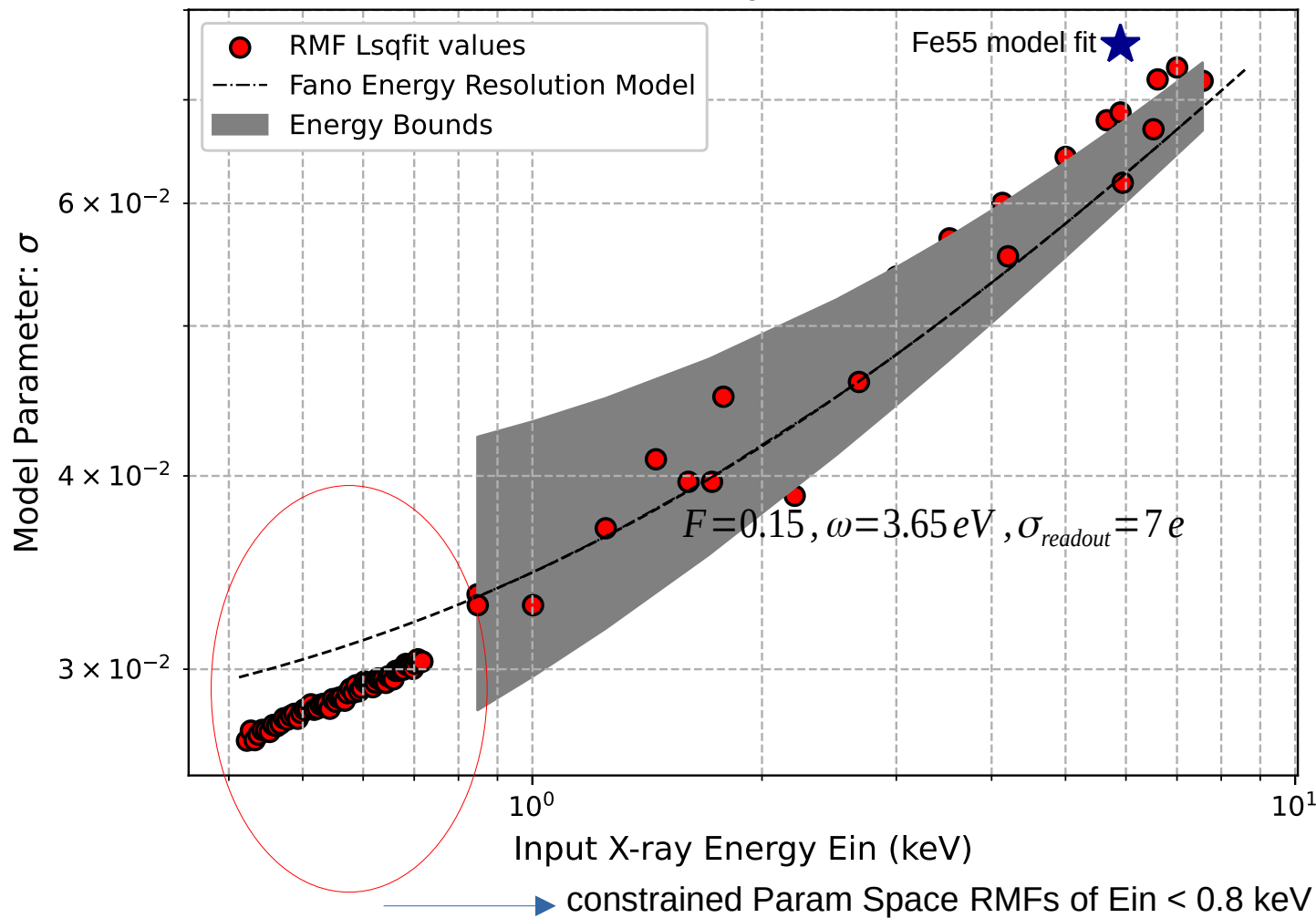
→ Loss function1
→ Loss function2

Strong Dependence / correlation between Params(tau,l) Params(f0,beta)

Used: Lsqfit, MCMC, MultiNest -> Not able to resolve

# Trying to contrain the Model Parameters through Manual fitting for Ein > 0.8 keV

Model Fit Trend Analysis of Parameter: σ

Legend:
- ● RMF Lsqfit values
- ·—·— Fano Energy Resolution Model
- ▆ Energy Bounds

Fe55 model fit ★

$F = 0.15, \omega = 3.65\,eV, \sigma_{readout} = 7\,e$

Model Parameter: σ

Input X-ray Energy Ein (keV)

constrained Param Space RMFs of Ein < 0.8 keV

Constrained Param Space RMFs of Ein < 0.8 keV

These are the fit values for RMFs below 0.8keV and they represent the current RMFs quite well. So we can say this param space is well constrained.

But still we need to figure out how they have changed or would be for updated RMF
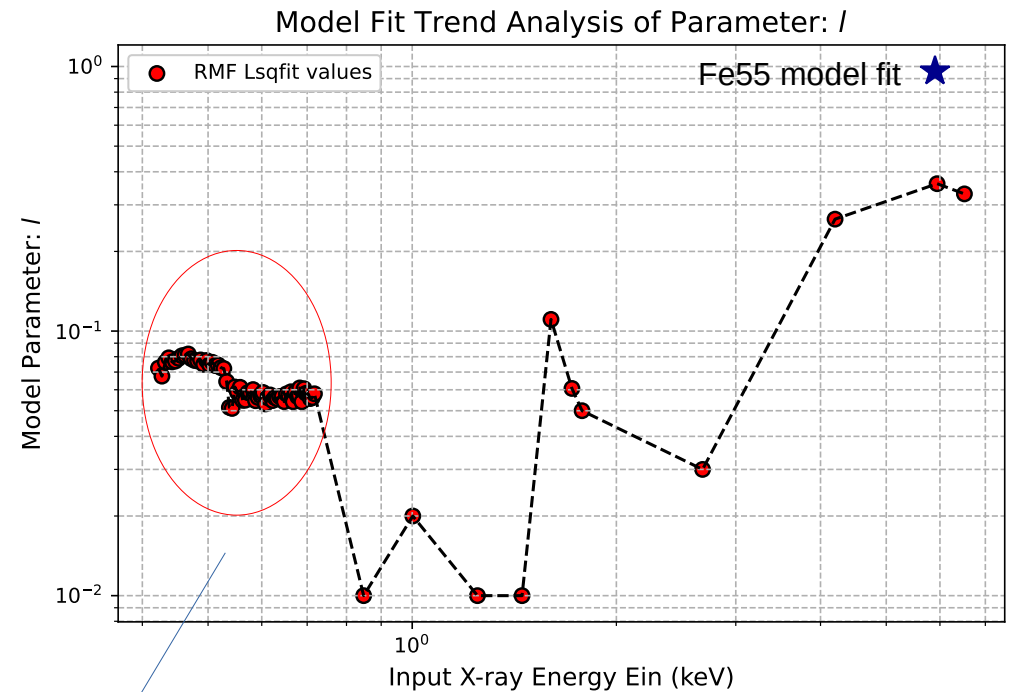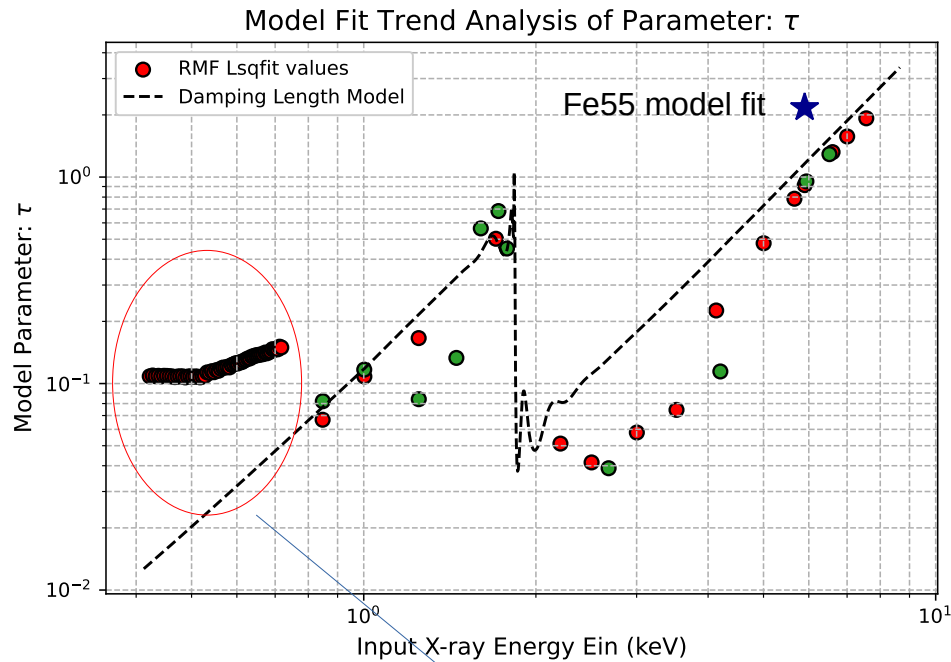
Constrained Param Space RMFs of Ein < 0.8 keV

For Ein>0.8; Tried several ways of constraining (fixing) one/many of the parameters.

1. Parameter l fixed to 0.1 micro meters (ref.)
2. Parameter sigma fixed to fano factor estimation.
3. Parameter tau fixed to Normalized Damping length model. (**Result:** From my Analysis when Main Peak is Purely Gaussian (no shoulder) l/tau follows Normalized Damping length model)

Model Fit Trend Analysis of Parameter: $f0$

Model Fit Trend Analysis of Parameter: β
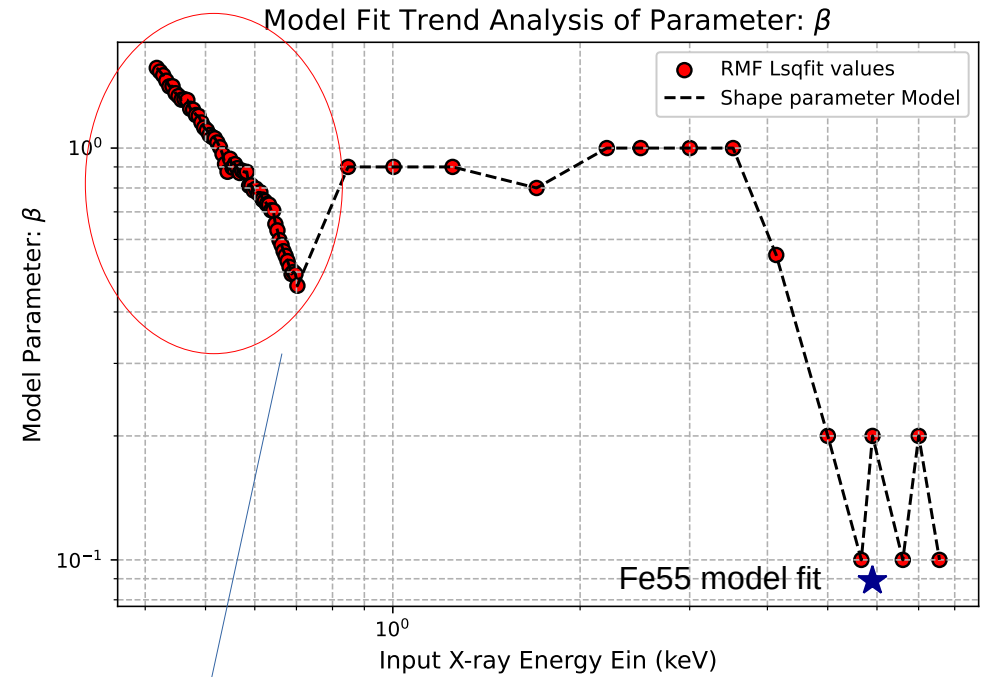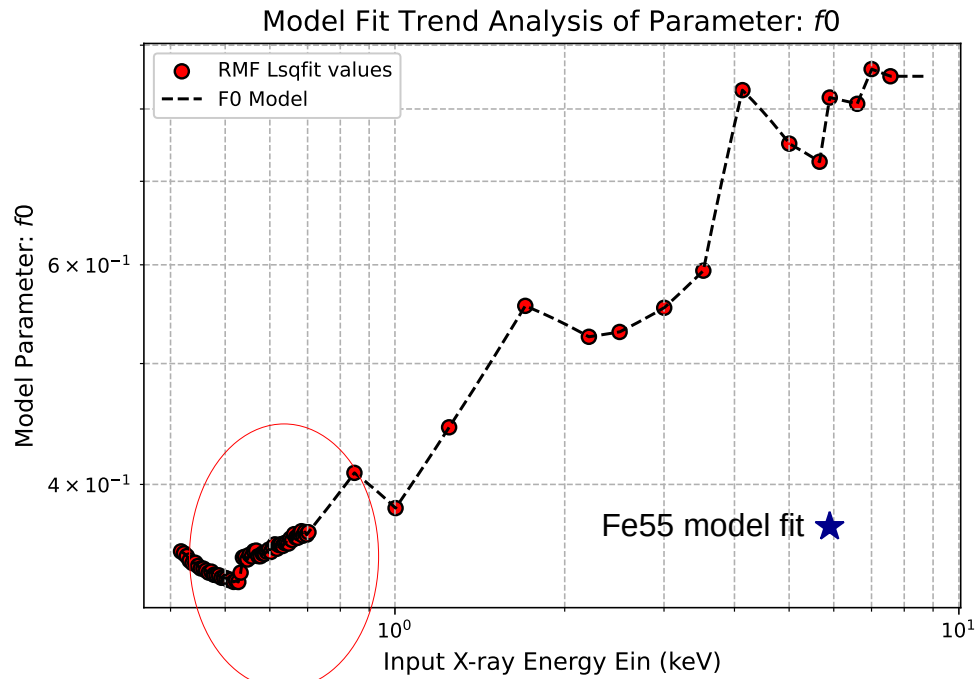
Constrained Param Space RMFs of Ein < 0.8 keV

What can be definitevely said? f0 and beta very higly correlated.
Have multiple combinations to represent the RMF
f0 -> Extend of the shoulder along energy
beta -> shape of the shoulder

Extra slides